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A Field Test Using Coal:dRDF Blends in Spreader Stoker-Fired Boilers

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16. ABSTRACT

This program was conducted to characterize and demonstrate the technical, economic, and environmental feasibility of combustion densified forms of refuse derived fuel (dRDF) blended with coal in spreader stoker-fired boilers. A total of 258.5 Mg (285 tons) of pelletized 1/2-inch-diameter x 3/4-inch-long dRDF was co-fired with coal in 2.7 x 7.5 kg/sec (60,000 lb/hr) and 3.6 x 10 kg/sec (75,000 lb/hr) of 1.03 MPa (150 psig) saturated steam. The results indicate that coal:dRDF blends up to 1:2 can be handled and burned in conventional spreader stoker-fired boilers without major equipment modification. As more dRDF was substituted for coal, the flame volume increased, the opacity decreased, the fly ash carbon burnout improved, and the turndown ratio of boiler operation increased. The emissions from the blend firing decreased slightly in mass flux, dropped significantly in particulate size and stack opacity, and had satisfactory particulate resistivities.

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A FIELD TEST USING COAL:dRDF BLENDS IN SPREADER STOKER-FIRED BOILERS

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

In recognition of the fact that more than 50 percent of the roughly 42,000 industrial boilers in the U.S. are coal-fired boilers, the Environmental Protection Agency undertook a project to investigate the technical and environmental implications of using densified (pellet form) refuse derived fuel as a substitute for stoker coal. This report presents the results from co-firing 258.5 Mg (285 tons) of dRDF when firing at various volumetric blend ratios of coal:dRDF, i.e., 1:1, 1:2, and 0:1.

The investigation specifically addresses the performance of the fuel handling and feeding system, the boiler, and the resulting emissions from each blend firing. Since a spreader stoker-fired 7.6 kg/sec (60,000 lb/hr) boiler was co-fired for 230 hours (132 hours continuously) without major difficulty, the results are sufficiently encouraging to suggest a larger term demonstration of co-firing coal and dRDF.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This study program was initiated with the overall objective being to characterize and demonstrate the technical, economical, and environmental feasibility of combusting densified forms of refuse derived fuels (dRDF) blended with coal in spreader stoker-fired boilers.

The testing was conducted at the Maryland Correctional Institute Power House located in Hagerstown, Maryland. A total of 258.5 Mg (285 tons) of pelletized 1/2-inch-diameter by 3/4-inch-long dRDF was co-fired with coal in spreader stoker boilers rated at 7.6 and 9.9 kg/sec (60,000 and 75,000 lb/hr) of 1034 kPa (150 psig) saturated steam.

The field tests were designed to investigate (1) the material handling characteristics of dRDF, i.e., storage in warehouses, drop boxes, and open slabs; conveying; and feeding out of bunkers; (2) boiler performance, i.e., boiler efficiency, spreader limitations, grate speeds, underfire and overfire air requirements, steam production, flame impingement, slagging, fouling, clinkering, and combustion gas analysis; and (3) environmental performance, i.e., size, mass, opacity, and resistivity of particulates; gaseous (SO_x, NO_x, Cl, F, Hc) emissions; and trace organic and inorganic emissions.

With the steam demand limiting the test boiler to a 30-55 percent load, the 258.5 Mg (285 tons) of dRDF were satisfactorily co-fired with coal for 230 hours (132 hours continuously). The results indicate that coal:dRDF blends up to 1:2 can be handled and burned in conventional spreader stoker-fired boilers without major equipment modification. The fuel blends were handled satisfactorily, although some pellet deterioration (due to excessive handling and rain damage) caused much dusting and slightly impeded the pellet flow. After adjustments of the air controls, the spreader-feeders, and the grate pulse interval, the blends generally burned as well as coal alone. Moreover, as more dRDF was substituted for coal, the flame volume increased, the opacity decreased, the fly ash carbon burnout improved, and the turndown ratio of boiler operation increased. Relative to the particulate emissions from coal-only firing, the emissions from the blend firing decreased slightly in mass flux, dropped significantly in particulate size and stack opacity, and had resistivities within the range for satisfactory electrostatic precipitator performance. Also as dRDF substitution increased, chlorine and trace metals (specifically Pb, Sb, Br, and Mn) increased, and SO_x decreased correspondingly.

This report was submitted in fulfillment of Contract No. 68-03-2426 by Systems Technology Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period June 29, 1976 to December 30, 1977.

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SECTION 1

INTRODUCTION

FEASIBILITY OF BURNING DENSIFIED REFUSE DERIVED FUEL (dRDF)

During the first half of the 1970's, several short-duration, coal-dRDF test burns had indicated that it may be feasible to use dRDF as a substitute for stoker coal. However, while these tests have provoked the interest of the resource recovery community, they have failed to answer the questions most critical to determining this feasibility:

1. Can dRDF be burned within existing environmental constraints?
2. Does dRDF burning have any detrimental effects on a boiler system or its performance?
3. Is dRDF an economical substitute for coal?

The present study was designed to explore the answers to the boiler performance questions (Section 4) and the environmental questions (Section 5). The economics of producing dRDF was addressed by the National Center for Resource Recovery, Inc. (NCRR), under Grant Number 804150.

TYPES OF REFUSE FUELS

Beginning in the 1950's in Europe and in the late 1960's in the United States, the technical community has had an increasing interest in the fuel value of urban solid waste. As a result of this interest and the impetus caused by the energy crisis of 1973, four basic types of solid waste fuels have been developed: (1) unsorted urban refuse, (2) fluff refuse derived fuel (fluff RDF), (3) powdered refuse derived fuel (powdered RDF), and (4) densified refuse derived fuel. Unsorted urban refuse, the oldest type, is thermally processed in mass-burning incinerators. This type of facility usually excludes such bulky objects as applicances, rolled carpets, and furniture. Fluff RDF is produced by shredding mixed urban refuse and passing the milled material through a series of material separation steps to remove many of the noncombustibles. Powdered RDF is usually produced by an acid-embrittling and hot-milling drying operation. Densified RDF is produced from either fluff or powdered RDF with equipment such as pelletizers, brickquetters and cubetters. The dRDF is intended for plants which generally burn lump-sized coal, such as industrial or institutional stoker-fired plants, rather than plants which burn pulverized coal.

PREVIOUS dRDF TEST PROGRAMS

Perhaps the first summary of the early programs to investigate the feasibility of burning dRDF with coal was a report by R. T. Stirrup, Fellow of the Institute of Public Cleansing and Director of Public Cleansing, City of Southford, England. Published in 1965, this report covers applied research in England and Europe during the 1956-1960 period. Specifically, it describes programs which prepared briquettes out of mixed refuse and co-fired the briquettes with coal to generate steam in short-term tests. One of these programs generated 3 pounds of steam for each pound of briquettes burned.

Since the early 1970's, several similar short-duration programs were conducted in the United States. Table 1 lists these programs, and Appendix H details the results of each.

CURRENT dRDF TEST PROGRAM

Since most of the previous programs had test firings lasting less than 12 hours, the EPA contracted with Systems Technology Corporation (SYSTECH) to conduct a comprehensive technical and environmental test program to determine the feasibility of co-firing dRDF and coal in spreader stoker-fired boilers.

SITE SELECTION

As an integral part of the Environmental Protection Agency (EPA) planning for the test program, the EPA awarded a grant to NCRR in Washington, D.C., to produce at least 907 Mg (1000 tons) of dRDF. Consequently, to keep costs within budget limits, the principal requirement in selecting a boiler plant for the test program was a site within a reasonable trucking distance of Washington, D.C.

A second requirement was that the site have a spreader stoker boiler which would be representative of many similar stoker-fired boilers. In addition, it should have a variable grate speed, an adequate fuel storage capacity, a feeding system, and other facilities readily adaptable to the testing requirements. A third requirement was a boiler plant with management sufficiently interested and cooperative to ensure the successful performance of the test program.

Accordingly, four boiler plants within a 241-km (150-mile) radius of Washington, D.C., were established as candidate sites. After SYSTECH engineers visited and evaluated each plant, the Maryland Correctional Institute (MCI) Boiler House in Hagerstown, Maryland, was selected as the testing site. This plant met the three requirements as follows:

1. The MCI plant had three Erie City Iron Works boilers rated at 3.1, 7.6, and 9.9 kg/sec (25,000, 60,000, and 75,000 lb/hr) of 1034-kPa (150-psi) saturated steam. The steam generation capacity was sufficient to ensure continued plant operation if a boiler should go off-line because of malfunctions due to dRDF burning.

TABLE 1. SUMMARY OF PREVIOUS CO-FIRING TESTS

	Location of test	Test sponsor (Producer)	Date of test	Type of dRDF	Vol blend coal:dRDF	Amt dRDF fired	Test duration
1.	Fort Wayne, Ind. Municipal Power Plant	National Recycling Center	1972	cubette 1 1/2" × 1 1/2" × 2"	3:1	36 Mg	---
2.	Sunbury Steam Electric Station, Pennsylvania Power & Light	(Elo & Rhodes)	1975	5/8" pellets	---	73 Mg	2 days
3.	Piqua, Ohio, Municipal Power Plant	Black-Clawson Fibreclaim, Inc.	1975	3/8" pellets	1:1	20 Mg	7 hr
4.	Wright-Patterson Air Force Base	Air Force Black-Clawson Fibreclaim, Inc.	1975	3/8" pellets	1:1 1:2	36 Mg	34 hr 6 hr
5.	Eugene Water & Electric Board	Sandwell International, Inc. (Vista)	1974	3/8" pellets	---	19 Mg	1 1/2 hr
6.	University of Wisconsin Oshkosh, Wisconsin	Wisconsin Solid Waste Recycling Authority (Vista)	1976	1 1/8" pellets	1:1, 1:3, and 0:1	19 Mg	---
7.	Appleton Diversive	Wisconsin Solid Waste Recycling Authority (Grumman)	1976	3/4" pellets	---	36 Mg	8 hr
8.	Menasha Paperboard Mill	Wisconsin Solid Waste Recycling Authority (Grumman)	1976	3/4" pellets	3:2	19 Mg	---
9.	Chanute Air Force Base	U.S. Army CERL (Vista)	1975	1 1/8" pellets	1:1 0:1	136 Mg	---
*10.	Waupun, Wisconsin	Wisconsin Solid Waste Recycling Authority	1976	3/4" pellets	20%, 30%, and 40% by heating value	19 Mg	---
*11.	Green Bay, Wisconsin	Ft. Howard Paper (Grumman)	1976	3/4" pellets	1:3 1:2	36 Mg	
*12.	Stockertown, Pennsylvania	Hercules Cement (Vista)	1975	1 1/8" & 5/8" pellets	---	182 Mg	7 days

* Appendix H does not include a discussion on these tests.

2. The plant could accommodate all of the test equipment and procedures. All flows in and out of the boiler were readily accessible. The coal silo system could be easily bypassed to permit installing a temporary coal-dRDF fuel handling system.

3. The plant management expressed sufficient interest and willingness to cooperate in the test program.

TEST PROGRAM OUTLINE

The test program consisted of four separate field tests: (1) co-firing coal and 20.9 Mg (23 tons) of dRDF in a series of short runs during December 1976, (2) a coal base test in January 1977, (3) co-firing coal and 106.1 Mg (117 tons) of dRDF in a series of longer duration tests during March 1977, and (4) co-firing coal and 127.9 Mg (141 tons) of dRDF also in a series of longer duration tests coupled with electrostatic precipitator (ESP) evaluations during May 1977.

Throughout each test, SYSTECH engineers monitored and evaluated the fuel handling system, the boiler performance, and the stack emissions.

While Section 2 presents a summary and conclusions from the program, Sections 3, 4, and 5 describe each phase and aspect of the test program and evaluate the results for each.

SECTION 2

SUMMARY AND CONCLUSIONS

INTRODUCTION

Densified refuse derived fuel may be considered one of the more marketable products recovered from municipal solid waste. When densified in the form of pellets, cubettes, or briquettes, it may be handled, transported, and fed separately or blended with coal and burned in existing stoker-fired boilers without major equipment modification.

Over the past few years, several limited tests have tentatively confirmed that dRDF is a viable coal substitute. While these tests produced positive results, boiler monitoring and emission tests were performed only in a few instances.

As a result of these encouraging tests, the Environmental Protection Agency sponsored two parallel efforts: one to determine the economics of preparing dRDF and the second to assess the technical and environmental implications when the fuel is used as a coal substitute. This report presents the technical and environmental evaluation of co-firing tests conducted at the Maryland Correctional Institute power plant in Hagerstown, Maryland. The dRDF used in these test were pellets prepared by the National Center for Resource Recovery under a research grant.

TEST OBJECTIVE

The objective of the study was to determine, characterize, and demonstrate the technical and environmental feasibility of combusting dRDF with coal in spreader stoker-fired boilers. The tests were to be conducted in a stoker-fired boiler which would have a rating between 3.1 and 25.1 kg/sec (25,000 and 200,000 lb/hr) of steam and would be within 241 km (150 miles) of NCRR in Washington, D.C. The study was to specifically address fuel handling, boiler performance, and environmental effects when dRDF pellets, cubettes, and briquettes were fired with coal.

SITE SELECTION

After all the candidate boiler plants within 241 km (150 miles) of Washington, D.C., were surveyed, the MCI plant was selected because it met the above described criteria most satisfactorily. This plant had three Erie City Iron Works boilers, one each rated at 3.1, 7.6 and 9.9 kg/sec (25,000, 60,000, and 75,000 lb/hr) of 1034 kPa (150 psi) saturated steam.

TEST DESIGN

The test was designed to combust 258.5 Mg (285 tons) of dRDF during 236 hours of firing various blend ratios of coal:dRDF. These tests were conducted in a series of burns with volumetric coal:dRDF ratios of 1:1, 1:2, and 0:1 and with test durations ranging from 20 minutes to 132 hours. The series of coal:dRDF tests were preceded and followed by a coal-only test with duplicate conditions. Also, because of required plant steam demand, all of the tests were conducted at only 30 to 55 percent of boiler design capacity. The initial tests were designed to ensure that dRDF could be safely burned without jeopardizing the boiler's capability of meeting the steam demand. These tests included monitoring the performance of the spreaders while introducing dRDF into an unfired boiler and a series of short-duration burns to determine the combustion properties and the boiler performance. Subsequent field tests involved a study of (1) the material handling characteristics of dRDF, i.e., storing, conveying, feeding out of bunkers, etc.; (2) boiler performance, i.e., grate speeds, underfire and overfire air requirements, steam production, spreader limitations, boiler efficiency, flame impingement, slagging, fouling, clinkering, combustion gas analysis, etc.; and (3) environmental performance, i.e., particulates, gaseous emissions, and trace organic and inorganic emissions. Since only pelletized dRDF was available, testing with cubettes and briquettes was not conducted.

TEST RESULTS

Material Handling

Throughout the field testing, 259 Mg (285 tons) of dRDF were received, stored, and conveyed to the boiler without major difficulty or malfunction of the fuel handling system. Difficulties were limited to dusting and pellets hanging up in feed hoppers.

Pellet Storage--

At successive periods, the pellets were stored in 20-cubic-yard open containers, in a warehouse (uncovered), and on an outdoor concrete slab (tarpaulin covered).

Twenty-Cubic-Yard Containers--Since the pellets received during the winter tended to steam, they eventually froze into a solid mass. Minimal rodding, however, broke up the frozen pellets, and subsequent handling further restored the individual pellet integrity without significant degradation to the pellet.

Warehouse--Approximately 125 Mg (140 tons) of pellets were stored in an unheated warehouse for 2 months. With the exception of mild odors and some fungus growth, this storage proved to be the most effective in maintaining pellet integrity over extended periods of storage time. Since the depth of the piles was limited to 1.8 m (6 ft), increases in temperature due to composting effects were negligible, and the pile temperature stabilized at 60°C (140°F).

Open Slab--The pellets stored in the warehouse were subsequently moved to an outdoor storage area. The pellets were stored in 1.8-m (6-ft) piles on an outdoor slab and covered with a tarpaulin. Moisture accumulation under the tarpaulin caused pellets at the top of the piles to deteriorate and cake. Also, some pellets sustained minor damage, i.e., swelling and roughened edges, because of water infiltration onto the slab.

Pellet Feeding--

The pellets were conveyed to the boiler feed hopper by a temporary fuel blending and handling system. The coal and dRDF were volumetrically blended in the various ratios by separately feeding coal and pellets from two hoppers to a common bucket elevator which subsequently conveyed both coal and pellets to a weigh lorry. The fuels were volumetrically blended by filling the feed conveyors to capacity (level with the conveyor flights) and operating the coal and pellet feed conveyors at speeds commensurate with the desired blend ratio, i.e., a 1:2 coal:dRDF blend would require the dRDF conveyor to run at twice the speed of the coal conveyor. Although this feeding system generally worked well, it had some difficulties with deteriorated pellets. As the amount of fines increased (due to excessive handling), the pellets would not flow from the feed hoppers without rodding. These fines also caused considerable dusting throughout the plant. This dusting was subsequently controlled by installing a steam jet at the conveyor transfer point.

Pellet Properties--

The 1/2- × 3/4-inch pellets had an average bulk density of 425 kg/m^3 (26.5 lb/ft^3) and ranged from 400 to 466 kg/m^3 (25 to 29 lb/ft^3). The material density for intact pellets ranged from 1.22 to 1.34×10^3 kg/m^3 (76 to 84 lb/ft^3) while that for deteriorated pellets averaged 0.98×10^3 kg/m^3 (61 lb/ft^3). The as-received properties were 12.10 to 15.12 MJ/kg (5200 to 6500 Btu/lb), 20 to 29 percent ash, 9 to 10 percent fixed carbon, 12 to 13 percent moisture, 50 to 57 percent volatiles, and 1142°C to 1152°C (2088° to 2105°F) hemispheric reducing fusion temperatures. NCRR projected that further processing of the shredded refuse to remove glass and other inerts could produce a pellet with a heat content of 19.1 MJ/kg (8200 Btu/lb) and an ash of 10 to 12 percent.

Boiler Performance

Spreader-Feeder Performance--

In a cold flow run (furnace not fired) to test the fuel distribution of the Hoffman Combustion Engineering spreader-feeders, two different sized pellets were distributed onto the grate: 1/2 × 3/4 and 1 × 2 (diameter × average length in inches) pellets. Because the Hoffman spreader throat has a maximum size restriction of 1 1/2 inch, the 1-inch-diameter by 2-inch-long pellets tended to hang up and slug-feed the furnace. However, the 1/2-inch-diameter by 3/4-inch-long pellets generally were handled and fed well with the larger pellets traveling to the rear of the grate and the fines falling close to the spreader. During the initial combustion tests with 100 percent pellets, the spreader had to be adjusted to decrease the pellet trajectory in the furnace by approximately 0.3 m (12 in.). In addition, the maximum steam load that the boiler could carry was 6.8 kg/sec (54,000 lb/hr) or 70 percent of design capacity. This derating is the direct result of volumetric limitations of the spreader feeder.

Combustion of dRDF--

While operating at these partial boiler capacities, the combustion of the various blends of coal:dRDF was generally as good as the combustion of coal only. However, when the dRDF substitution was increased, the flame length, intensity, and volume of the fireball increased correspondingly. As the intensity of the fireball grew, the flame temperature, measured about 1.5 meters above the center of the grate, also increased from 1200°C (2192°F) for 100 percent coal firing to 1240°C (2264°F) for 100 percent dRDF firing.

When test firing the 1:1 blend and 100 percent dRDF, the fireball was kept well away from the rear wall of the furnace by adjusting the overfire air. Once these jets were adjusted for minimum smoke and maximum efficiency for coal-only burning, they continued to meet the mixing and wall protection requirements when burning blends and 100 percent pellets. As viewed from the side of the furnace when firing both pellets and blends, the bed was well burned out by the time it approached the front ash pit. The flame pattern above the grate indicated that the fuel bed was maintaining proper porosity with minimum clinkering or agglomeration. This operation was achieved when burning a double screened, high ash fusion temperature 1370°C (2498°F) coal. With little attempt to optimize the system, a 10 to 12 percent carbon dioxide content in the flue gas at the boiler outlet was readily obtained.

Fouling--

Inspection of the furnace interior after the tests revealed that a light coating of ash had accumulated on the tubes. Also, an interim boiler inspection revealed that one-third of the rear wall of the boiler was covered with slag. This slagging was subsequently eliminated when a spreader was adjusted to prevent pellet impingement on the rear wall. Subsequent inspections of the boiler after being on-line for 8 days revealed that the slag had sloughed off.

Clinkering--

During the initial tests frequent clinkering occurred on the grate when firing a 1:1 blend. This clinkering was subsequently attributed to a low hemispheric fusion temperature, 1204°C (2200°F), of the coal. When the coal was changed to one having a higher ash fusion temperature, 1373°C (2500°F), the clinkering stopped. While coal with low fusion temperatures clinkered, the 100 percent pellets, which had a low fusion temperature of 1151°C (2103°F), did not clinker. This observation is valid within the constraints of the test conditions, i.e., a 4-hour test burn at a boiler capacity of 30 percent of rated design capacity and 100 to 130 percent excess air.

Corrosion--

Eight clamp-on corrosion test specimens were installed on the supply tubes of the rear screen wall 1.5 m (5 ft) above the fuel bed. After 478 hours of exposure to various blend and coal-only firings, normal wastage (less than 5 mils per year) was evident on all specimens except the 1018 specimen. This test specimen, which had extremely high metal wastage, was mounted in the area where the heavy slagging occurred because of the maladjusted spreader.

Boiler Operation--

Air Flow Controllers--During periods of load shedding, the fuel bed was more susceptible to clinkering when coal:dRDF blends were fired. The clinkering was eliminated by biasing the underfire air control to supply approximately 70 percent excess air to the fuel bed. On the basis of these results, boilers which are tight (minimum air leaks) should be capable of satisfactorily burning coal:dRDF blends with 50 percent excess air.

Oscillating Grate Dwell-Shake--Throughout the test, the duration and amplitude of the grate shake pulse was adjusted to advance the fire line at the rear of the boiler approximately 15.2 cm (6 in.) per excitation. In all advances, the pulse frequency was the principal controlling variable. At 40 percent load, the frequency of the pulse decreased from 11 minutes for 100 percent coal to 3 minutes for 100 percent pellets. When firing a blend, the pulse duration tended to increase because the bulk density of the blend ash was less than that of the coal ash.

Ash Handling--

Bottom Ash--The sieve analysis of bottom ash samples taken during blend firings indicated that conventional pneumatic ash handling systems should be able to handle the bottom ash from blend firings as well as they do the bottom ash from firing coal-only. On a few occasions fire occurred in the bottom ash hopper during blend firing. Rodding of the clinkers in the ash hopper revealed that the ash had a taffy-like consistency. Under similar conditions, when firing coal only, the bottom ash was much easier to break up by rodding.

The bottom ash removal system malfunctioned only during 100 percent pellet firing. The bottom ash was so fine that it would not de-entrain properly in the cyclone. The particles, which had been wetted by the steam in the vacuum ejector, passed through the cyclone and eventually plugged the ejector.

Dust Collector Ash--As dRDF was substituted for coal, the fly ash particles became finer. The size of the particles in the dust collector ranged from 200 micrometers for 100 percent coal firing to 90 micrometers (sizes at the 50th percentile) for 100 percent pellet firing. Also, the carbon content of the fly ash decreased significantly with increasing dRDF substitution. The primary factor contributing to this occurrence was the low fixed carbon content of dRDF (12 to 18 percent) compared to coal which had 65 to 85 percent fixed carbon.

Mass and Energy Balance--

Mass Balance--The mass balance indicated that an unusually large amount of the fuel ash had accumulated in the collectors. Subsequent analysis of the collector fly ash revealed that the high collector ash weights were due to the presence of 50 to 70 percent carbon in the collector ash. Also, since 90 percent of the particles exiting the boiler were greater than 50 micrometers in diameter, these large particles were removed by the cyclone. The carbon content of the bottom ash varied from 2 to 10 percent, and the carbon content of the stack fly ash (not captured by the cyclone) was 30 to 40 percent. The analysis of the stack fly ash as a function of blend revealed that its carbon content decreased as the dRDF substitution increased.

Efficiencies--During the testing the boiler efficiencies were extremely low, namely 55 to 60 percent. When the boilers were installed in 1963, they produced a boiler efficiency of 79 percent at an excess air of 34 percent and rated design capacity. These low efficiencies were primarily due to the low boiler loads (less than 30 percent of rating), high excess air (80 to 115 percent), and extremely high losses of combustibles in the refuse (up to 25 percent). The analysis of the results indicated that the coal-only and blend firing efficiencies had no discernable differences. However, this observation may be unique to the boiler installation at MCI since the large amount of unburned combustibles removed by the collectors is certainly an anomally to expected boiler performance.

Environmental Performance

Data Normalization--

Since the co-firing tests spanned a 6-month period, the properties of the coal and dRDF burned in the successive tests varied widely. The boiler excess air in the tests also varied considerably. To eliminate the effects of these variables, all the emissions data were corrected to 50 percent excess air and then normalized to a reference coal and dRDF composition. All the co-firing emissions data were then statistically compared with a coal-only baseline plot of emissions concentration versus boiler load. If the co-firing emissions data fell outside the 90 percent confidence limits for the coal-only emissions data, they were considered to be significantly different.

Particulate Emissions--

Mass Concentration--The particulate mass concentration (grams/standard cubic meter, g/scm) in the 1:1 and 1:2 blend firings was slightly less than in the coal-only firing. However, the reductions were not significant at the 90 percent confidence level. The mass flux at a 40 percent boiler load for 1:1 and 1:2 blend firings averaged 0.45 g/scm corrected to 12 percent CO_2. The coal fired during these tests was a nominal size of 1 1/4 × 1/4 inch with a maximum of 30 percent passing through a nominal 1/4-inch screen.

Particulate Size--As more dRDF was substituted for coal, the particulate diameter decreased. In the May tests, the diameters for the coal-only firings were 3 micrometers, and those for the dRDF-only firings were 0.8 micrometer (at the 50 percentile point).

Particulate Resistivity--Because of the unusually high carbon content in the fly ash during the coal-only firing, the resistivity was generally less than 10^6 ohm-cm. As dRDF was substituted for coal, the carbon burnout in the fly ash improved, and the resistivity increased to 2×10^{10} ohm-cm for the 1:1 blend firing.

Electrostatic Precipitator Performance--A mobile 5-cell electrostatic precipitator (owned by the EPA Industrial Environmental Research Laboratory in Research Triangle Park, North Carolina) was evaluated to determine the effect of dRDF on ESP performance. The evaluation, however, could not be conclusive because of short circuiting within the ESP. This short circuiting developed when the dielectric blocks from which the electrodes were suspended became coated with high carbon content aerosol. Appendix E discusses the test results.

Opacity--As dRDF was substituted for coal, the overall opacity of the plume reduced significantly. At 40 percent boiler load, the opacity for coal-only firing was 16 percent (based on a 1.22-m (4-ft) diameter stack). At the same boiler load and excess air, the opacity was only 10 percent for dRDF-only firing.

Gaseous Emissions--

SO_2--Since the dRDF had a sulfur content of 0.4 percent, the SO_2 emissions reduced with increasing dRDF substitution. The decrease was particularly significant for the 1:2 and 0:1 (100 percent dRDF) blend firings. At 40 percent boiler load and the same excess air levels, the SO_2 dropped from 1300 ppm for coal-only firing to 250 ppm for dRDF-only firing. This reduction in SO_2 follows exactly the reduction in sulfur content of the fuel (see Table 6 in Section 4).

NO_x--There were no significant changes in NO_x as dRDF was substituted for coal. At 40 percent boiler load and the same excess air levels, the NO_x concentrations ranged from 200 to 350 ppm with either fuel.

Chlorine--As dRDF was substituted for coal, the chlorine in the emissions increased from 60 ppm for coal-only firing to 650 ppm for dRDF-only firing. There appeared to be no appreciable change in chlorine concentrations as the load changed from 20 to 50 percent of design capacity.

Fluorine--Fluorine concentrations also increased with increasing dRDF substitution. However, the concentrations were very low, e.g., 8 ppm for coal-only firing and 12 ppm for dRDF-only firing at a 40 percent boiler load and constant excess air conditions.

Hydrocarbons--There were no significant changes in hydrocarbon emissions when substituting dRDF for coal. At a 40 percent boiler load, the total hydrocarbons ranged from 10 to 25 ppm. As the boiler load increased, the hydrocarbon concentrations decreased significantly. This reduction is probably attributable to the improved conbustion conditions at higher boiler loads.

Trace Organic and Inorganic Emissions--

Organic Emissions--The overall emissions of polycyclic compounds for coal-only and blend firings were well below the threshold limits proposed by the National Academy of Science. Typical measured values were: 543 ng/m^3 for anthracene/phenanthrene, 100 ng/m^3 for methyl anthracene, and 137 ng/m^3 for fluoranthene (all at 1:1 blend firing).

Inorganic Emissions--The analysis of the fly ash for trace metals revealed that relative to coal-only firing the blend firing enriched some metals but reduced others. For example, when firing a blend of 1:2 coal:dRDF, the amount of lead in the stack particulates was 8217 $\mu g/m^3$. This compares to a lead concentration of 230 $\mu g/m^3$ for coal-only firing. While dRDF was the main contributor of Br, Mn, Pb, and Sb, coal was the primary source of As, Ni, and V.

Several elements, particularly As, Ga, Na, and Sb, tended to concentrate in small particles. In addition, as the dRDF substitution increased, both the solubility of the fly ash and the amount of small-size particulates in the respiratory range increased. Consequently, each of these effects pose potential hazards from (1) respiration of heavy metals associated with aerosols and (2) leaching of high levels of heavy metals in landfills.

CONCLUSIONS

Fuel Handling System

Pelletized refuse can be stored, handled, and blended with coal in conventional material handling equipment provided the pellet structural quality is maintained. However, if pellets deteriorate because of excessive handling and exposure to rain, they will hang up in bunkers and will generate considerable dust as they are conveyed throughout the plant.

Boiler Performance

Boiler performance was evaluated at reduced load conditions, i.e., 30 to 55 percent of design capacity. At these boiler loads, some minor operational difficulties were encountered with slagging and clinkering throughout the testing. These difficulties were controlled by making simple adjustments. Typical adjustments included (1) biasing the air controls to higher excess undergrate air levels to prevent clinkering in the fuel bed during load shed, (2) properly adjusting the spreader feeders to prevent dRDF impingement on the side and rear walls of the furnace, and (3) setting the grate dwell and pulse intervals to compensate for the reduced ash bulk densities when the blends were fired. The boiler operation was restricted only when the spreaders and ash handling system became capacity limited during dRDF-only firing. The increasing dRDF substitution resulted in (1) improved carbon burnout in the fly ash, (2) decreased plume opacity, and (3) improved low-load performance (more than a 4:1 turndown without excessive smoking).

Environmental Performance

Compared to the particulate emissions from coal-only firing, the emissions from the blend firing decreased slightly in particulate concentration, dropped significantly in particulate size and stack opacity, and had resistivities within the range for satisfactory ESP performance. Of the gaseous emissions, SO_x decreased and chlorine increased, both significantly. Analysis of the trace inorganic elements in the fly ash when dRDF was fired revealed that concentrations of Pb, Cd, Mn, Zn, and Sb were significantly higher than other elements. Since the solubility of the fly ash increased with increasing dRDF substitution, landfilling the dRDF residue could result in hazardous levels of heavy metals in the leachate.

Summary

While the test was limited to firing at reduced boiler loads, the preliminary results from these field tests indicate that coal and dRDF can be co-fired at volumetric coal:dRDF ratios up to 1:2 with only minor adjustments to the boiler and fuel handling systems. Subsequent testing should address the long-term effects of corrosion and erosion on boiler tubes.

SECTION 3

MATERIAL HANDLING

The primary factors affecting the flow of a solid fuel through a material handling system are the following fuel properties: (1) size distribution, (2) moisture content (inherent and free), (3) bulk and particle density, (4) bulk compressibility, and (5) configuration and roughness. Previous tests at Chanute Air Force Base and the Pennsylvania Power & Light Company revealed that excessively handled dRDF becomes fluffy with increased fines which then promote high angles of repose and bridging in bunkers and hoppers. Since the handling and storage of the dRDF pellets at MCI required five separate fill/dump operations, similar dRDF deterioration and bridging were anticipated.

Therefore, to ensure that the plant would continually meet its steam load requirement and not have to be shut down because of blended fuel bridging in the bunker, the dRDF and coal blending and handling system was installed independently of the main coal feed system. Since the stoker spreader feeders might disperse the dRDF and coal blend differently than coal alone, the stoker spreader operation was monitored to characterize feeding behavior and dispersion of fuel on the grate for coal, a blend of coal and pellets, and pellets alone in a cold, idle furnace.

FUEL MECHANICAL PROPERTIES

Since the size and density of both the coal and the dRDF directly influence the performance of the fuel handling system, tests were conducted to quantify these properties. The following paragraphs discuss these properties.

Coal

Hoffman Combustion Engineering recommends that the coal fed to its spreader stoker have a nominal size of 1 1/4 × 1/4 inch with a maximum of 40 percent passing through a nominal 1/4-inch screen. A sieve analysis of the December coal showed that the distribution was 100 percent less than 3/4 inch with 70 percent passing through a 1/4-inch screen. Test firing of this coal showed that the high fraction of fines impeded proper plant operation, i.e., the fines caused furnace pressure pulsations as they entered the furnace, plugged the grate and air ports (larger size fines), and overloaded the fly ash system (smaller size fines). In view of the poor boiler system performance with the December coal, a double screened stoker coal had to be acquired before meaningful co-firing tests could be started.

Accordingly, arrangements were made with the Delta Coal Company (the supplier for MCI) to provide specification coal for the March and May tests. Although not standard fuel for the Hagerstown plant, the coal acquired was Swickley seam coal, a commercially available spreader stoker coal. The coal was obtained from the supply prepared for an industrial spreader stoker plant about 64 km (40 miles) from MCI.

The coal sieve analysis in Figure 1 compares the coal for the December and May field tests. The May size distribution is also representative of the coal for the March field tests. The January coal had a size distribution of 100 percent less than 1/2 inch with 70 percent passing through a 1/4-inch screen with an occasional 76-mm (3-in.) piece. The March and May coal was double screened, 1 × 0 Stoker coal with 30 percent passing through a 1/4-inch screen. The bulk density of the March and May coal averaged 777 kg/m^3 (48.5 lb/ft^3), and the material density ranged between 1.35 and 1.43×10^3 kg/m^3.

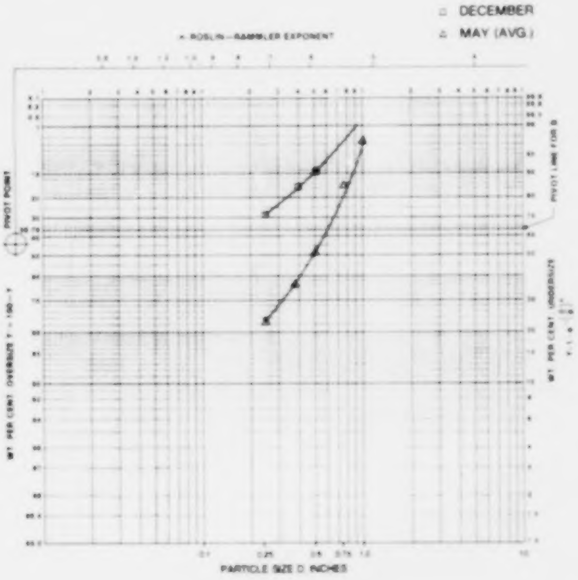

Figure 1. Comparison of the size distributions for the December and May coals.

Pelletized dRDF

The determination of the optimum pellet size was based primarily on obtaining a pellet that would fall in the middle of the recommended coal particle size range. The rationale for such a size was (1) to prevent the pellets from segregating from the coal during handling, (2) to ensure that the pellets would flow through the unmodified spreader without jamming, and (3) to spread the pellets onto the grate in a pattern similar to that of coal. Cold flow tests, i.e., feeding blends of coal:dRDF into the furnace without combustion or air flow, were conducted on nominal 1/2-inch-diameter by 3/4-inch-length and 1-inch-diameter by 2-inch-length pellets.

The test results indicated that the 1/2-inch-diameter pellets flowed satisfactorily through the material handling equipment and the spreader feeders. The 1-inch-diameter pellets tended to hang up in the spreader feeders and to slug feed the furnace. Since NCRR had a die available to produce the 1/2-inch-diameter pellets and they performed satisfactorily throughout the cold flow tests, only the 1/2- × 3/4-inch pellets were used in the combustion tests. Throughout the combustion tests, the pellets were sampled from the furnace hopper for length analysis. Figures 2 and 3 illustrate the length distribution data.

The March test pellets were stored in a warehouse and had a lesser deterioration and data spread than the May test pellets which were stored on an open slab. These discrepancies could be attributed to differences in the storage conditions and/or the original pellet characteristics. The pellet bulk density averaged 425 kg/m^3 (26.5 lb/ft^3) and ranged from 400 to 466 kg/m^3 (25 to 29 lb/ft^3). Bulk density was determined by filling and weighing a 1-ft^3 container and then subtracting the container tare weight. The material density for intact pellets ranged from 1.22 to 1.34×10^3 kg/m^3 while that for deteriorated pellets averaged 0.98×10^3 kg/m^3. Material density was determined by weighing a pellet and then determining the amount of volume displaced by the pellet when immersed in a liquid.

Figure 4 shows the bulk density of various coal:dRDF blends. The fact that the measured bulk density of the blend was higher than the arithmetic bulk density can be attributed to the dRDF particles filling the interstices in the coal and vice versa.

STORAGE OF dRDF

Throughout the pellet storage SYSTECH engineers were able to avoid spontaneous combustion by following the storage procedures for lignite. These procedures required keeping the storage period to a minimum and limiting the pellet piles to maximum depths of 1.8 to 2.4 m (6 to 8 ft).

Each of the field tests required 91 to 125 Mg (100 to 140 tons) of dRDF. Since the supply from NCRR was generally 11.8 to 14.5 Mg/wk (13 to 16 tons/wk), the deliveries had to be accumulated for 8 to 10 weeks before each test could be conducted. The pellets were transported from the NCRR test facility in Washington, D.C., to the Hagerstown, Maryland, plant in tarpaulin-covered, 20-yd^3, open roll-on containers. With deliveries from December 1976 through May 1977, the pellets acquired totaled 255 Mg (281 tons).

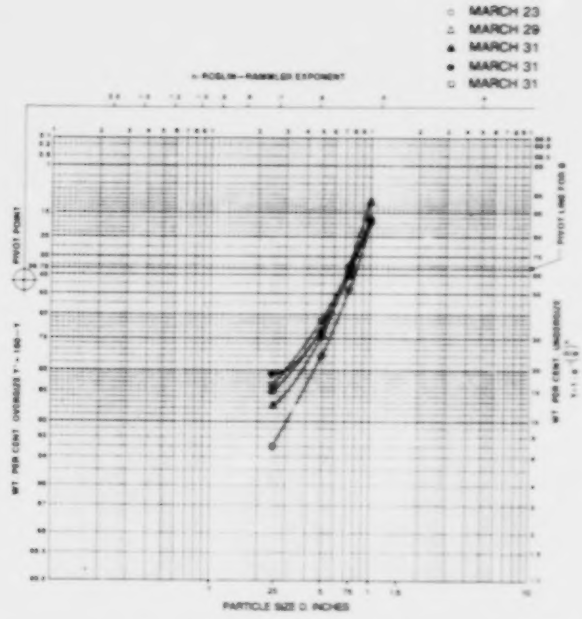

Figure 2. Characteristic length distributions for pellets burned in March.

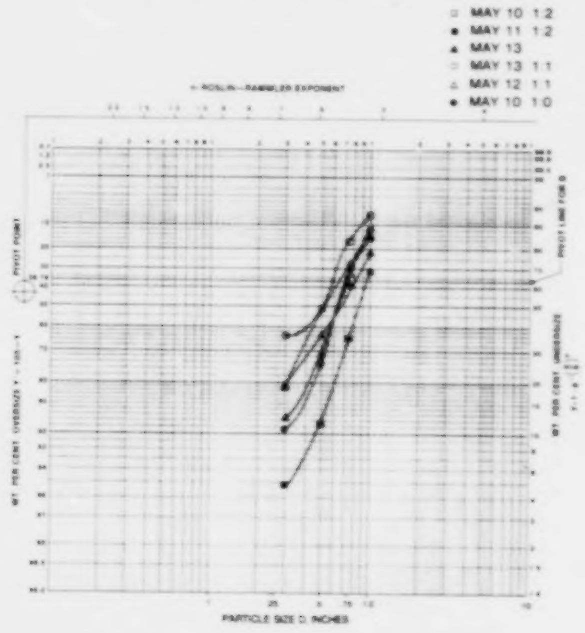

Figure 3. Characteristic length distributions for pellets burned in May.

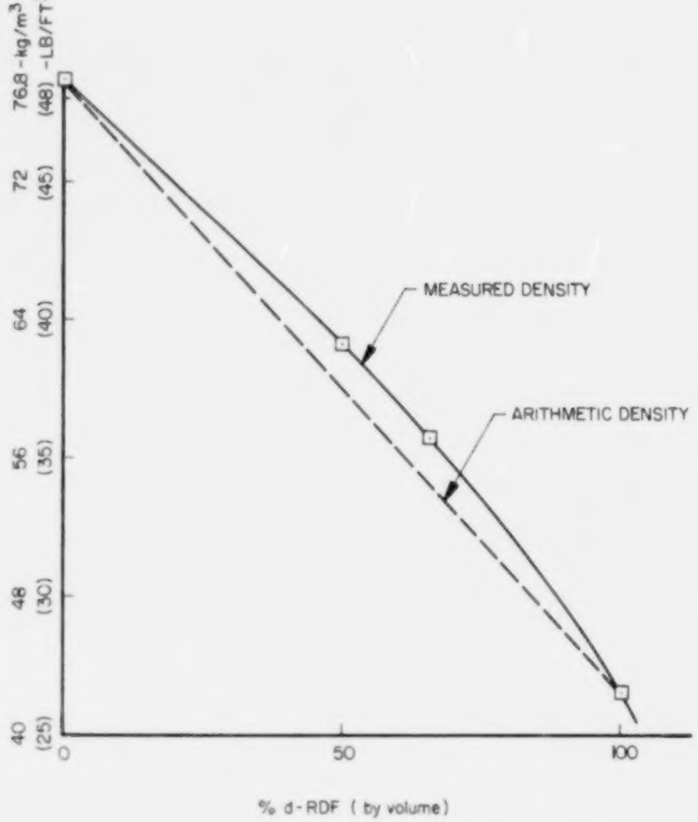

Figure 4. Comparison of arithmetic (interpolated) and field-measured blend bulk densities.

Since the slab beside the fuel handling system at MCI was too small to accommodate the pellet accumulations, the pellets were stored as follows: During December 1976 and January 1977, the pellets were kept in the roll-on containers until they were removed for burning. During February and March of 1977, the pellets were stored in an unheated warehouse within a residential community. With the advent of warmer weather and the possibility of offensive odors reaching the nearby homes, the pellets were subsequently moved to an open slab about a half mile from the MCI power plant and stored under a tarpaulin cover during April and May of 1977. The following sections discuss each of the storage conditions and their effects on the pellets.

Open Containers

When the pellets were stored in the roll-on containers during December 1976 and January 1977, they occasionally froze near the edges. Since the initially received pellets tended to steam, evaporating moisture trapped under the tarpaulin eventually froze the pellets into a solid mass. However, minimal rodding broke the mass into blocks which could flow freely. Subsequent movement broke up the blocks into individual pellets. Problems were also encountered with trash remaining in the containers from previous garbage loads. The contaminating trash included such materials as cans, cardboard boxes, and wood and metal pieces which had to be removed from the fuel to prevent their jamming the conveyors and/or the fuel spreader. While this problem was minimal (only 10 percent of the containers had such waste), it does demonstrate that care must be exercised in this area.

Warehouse

When the pellets were stored in the warehouse during February and March, they were dumped from the containers and pushed by a front-end loader into 1.8-m (6-ft) deep piles in the warehouse. In addition to mild odors, fungus growths appeared on the peaks of the piles or wherever there was a moisture vent. There did not appear to be any rodent or insect damage to the stored pellets. After the stored pellets were removed, the warehouse was easily cleaned.

Figure 5 indicates the extent of the pellet length reduction due to the warehouse storage. However, Figure 6 indicates that this reduction cannot be attributed to a moisture loss. A reasonable cause for the reduction could be the additional pellet handling and/or differences in the NCRR production procedures.

Remote Slab

When the pellets were stored during April and May on the open concrete slab at the MCI power plant, they were dumped from roll-on containers and then pushed by a front-end loader into 1.8- to 2.1-m (6- to 7-ft) deep piles on the slab. Although a plastic tarpaulin protected each pile from the weather, moisture accumulation under the tarpaulin caused pellet deterioration and caking (or capping) on the tops of the piles. A similar capping occurred on the piles stored in the warehouse. This caking consisted of a 5- to 10-cm (2- to 4-inch) thick layer in which the mechanical integrity of the individual pellets was greatly reduced. In addition, because of poor slab drainage, run-off water infiltrated some of the piles and deteriorated pellets on the slab surface. Such pellets swelled, and their initially smooth sides became rough. Figure 7 compares a deteriorated pellet with a good one. However, the deteriorated pellets were relatively few, and they were still usable although their rough sides impeded their flow out of storage bins. Rodding was required to assist the flow of these pellets from the storage bin.

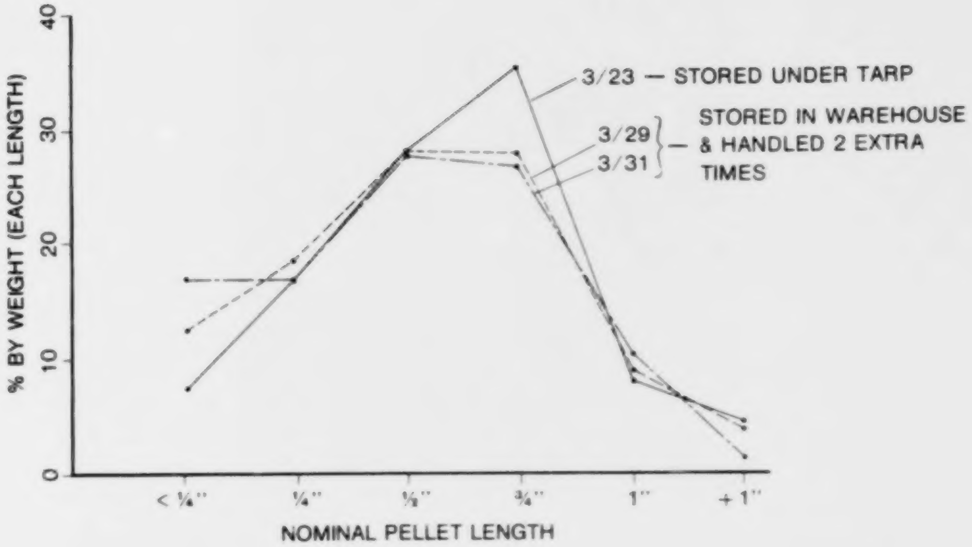

Figure 5. Comparison of pellet length distributions for different types of storage.

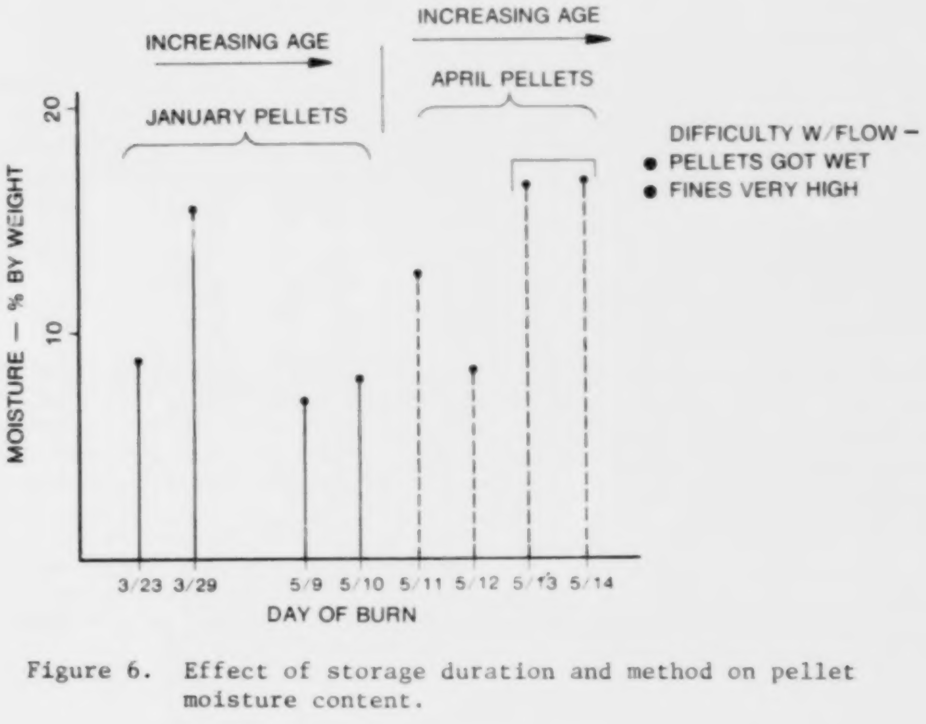

Figure 6. Effect of storage duration and method on pellet moisture content.

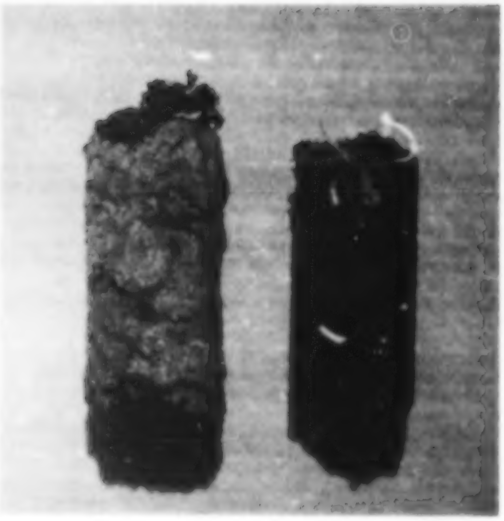

Figure 7. Comparison of a deteriorated pellet (left) and a well-formed pellet (right).

On-Site Slab

Some of the 35 Mg (40 tons) of dRDF remaining from the January and March tests and stored in the warehouse were transferred to the slab beside the fuel handling system at MCI for subsequent use during the May tests. These pellets were stored on the slab in a 2.4-m (8-ft) deep pile. The pile was periodically monitored with a thermocouple imbedded 1.5 m (5 ft) down from the top of the pile. After the pile temperature rose to 60°C (140°F), it dropped as the pile dried out to ambient temperature by the time of the May test.

FUEL HANDLING SYSTEM

Description

Coal is delivered to the Hagerstown plant in trucks which dump through a grizzly grate onto a drag chain feeder to the bucket elevator inlet. The bucket elevator delivers the coal to a square concrete silo. A "weigh lorry" on rails over the firing aisle and located above the stoker feeder hoppers transports the coal from the silo to the stoker feed hopper and then weighs and dumps the coal.

As noted previously, since the blended dRDF and coal fuel could have bridged the silo and thereby caused a plant shutdown, a temporary fuel blending and handling system was installed to bypass the silo during the field tests.

As shown in Figure 8, the system included a canopy-covered slab with storage space for about 27 Mg (30 tons) of both coal and pellets. The conveying equipment consisted of two 8-yd^3, pyramid-bottom bins that fed the fuel into cleated, pin-pan, Z-belt conveyors which in turn emptied the fuel into the feed hopper of a bucket elevator. Orbital vibrators were installed on the coal and pellet bins to facilitate free fuel movement. The bucket elevator had a straight back with the other three sides inclined at 45 degrees to feed the fuel into a 30-degree, 0.2-m (8-in.) square chute.

The starters on the Z-belt conveyors and the bucket elevator were interlocked. The activation of a single start button began the blend feed. The feed from the bins could be stopped from a station next to the weigh lorry or from outside the building next to the fuel bins. Normally the fuel feed was stopped and the elevator allowed to empty before a complete shutdown.

The coal and dRDF were blended to the various coal:dRDF ratios by changing drive pulleys to vary the speed of one of the Z-belt conveyors. The volume of fuel loaded per foot of conveyor was maintained by scraping the fuel load level with the top of the conveyor flights.

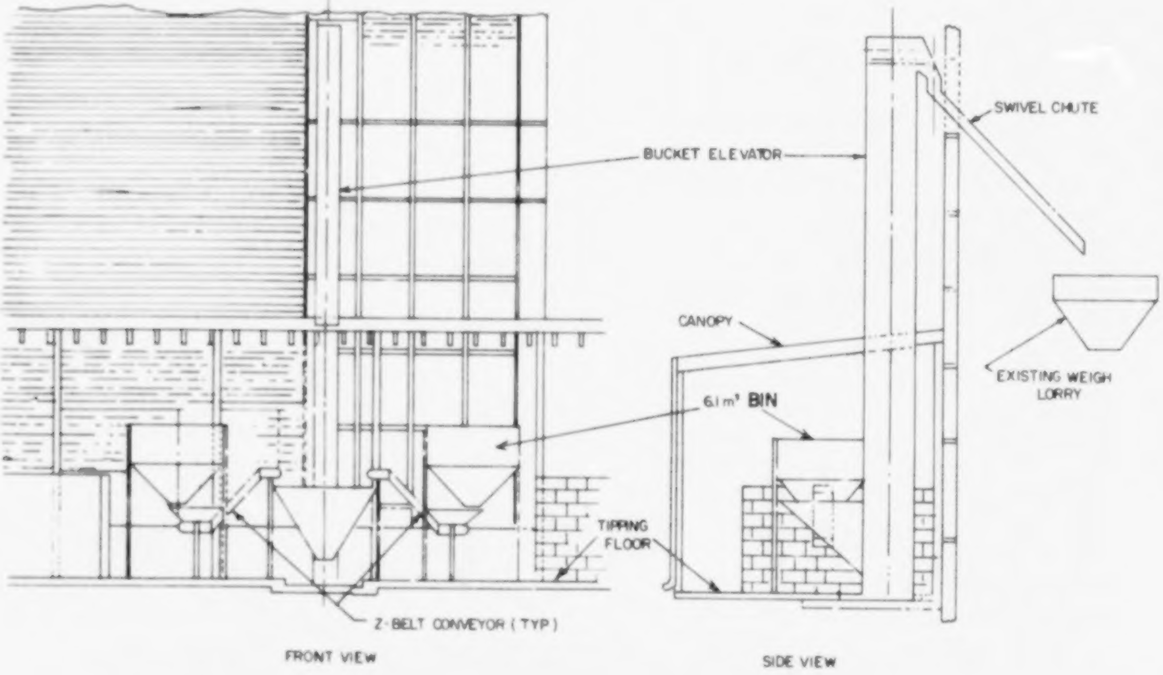

Figure 8. Front- and side-view drawings of the temporary fuel handling system.

The temporary blending and handling system could transfer 2450 kg (5400 lb) of a 1:1 coal and dRDF blend into the weigh lorry in approximately 30 minutes or at a rate of 1.39 kg/hr (3.1 lb/sec). The limiting factor on this rate was the speed of the Z-belt conveyors.

Operation

Two crews operated the fuel handling system. One crew, consisting of a truck driver and a front-end loader operator, retrieved the dRDF from storage and delivered it to the test site. The second crew consisted of two men at the test site, one was a front-end loader operator and the other was a helper. This crew filled the coal and dRDF bins after each loading to the weigh lorry.

Performance

In general, the temporary fuel blending and handling system performed well throughout the test program. The mixture of 1 × 0 coal with less than 30 percent fines and 1/2-inch-diameter × 3/4-inch-long pellets fed well and required less hoeing in the stoker feed hopper than coal alone. During the January and March field tests, the blend fed much easier than coal alone. However, near the end of the May field tests, the pellets would "rat-hole" (assume a high angle of repose) in the 8-yd^3 pyramid feed bins unless they were rodded periodically. The "rat-holing" was due primarily to pellets whose sides had become fluted because of water damage. Consequently, such pellets tended to interlock and bridge.

Lengths of pipe or chunks of blacktop (picked up by the front-end loader) intermingled with the pellets and jammed the Z-belt conveyors once or twice each 8-hr shift. While thorough cleaning of the transportation equipment and careful operation of the front-end loaders would have prevented the inclusion of these materials, a grizzly grate and a magnet, such as used in a coal plant, would have been a more practical means of preventing the introduction of such refuse into the fuel flow.

At the outset of the field tests, dust released during coal and dRDF fuel transfer from the bucket elevator chute to the weigh lorry was excessive. While a shroud over the chute initially contained the dust, the subsequent motion of the bucket elevator blew out the loose dust. The dust had a lint-like consistency and settled throughout the plant. Consequently, a hood was installed over the weigh lorry and coupled to what proved to be an inadequate exhaust fan. Although this installation provided some relief, the dust was still excessive until a steam jet was installed under the hood. This steam jet wetted the dust particles and adequately suppressed the dust from spreading throughout the plant.

To quantify the blending system performance, five fuel samples were taken from the feed trough (which filled the lorry) on each of two representative field test days. The samples, approximately 4.5 kg (10 lb) each, were hand-sorted into coal and pellets, and the two sorts for each sample were weighed. The remaining dust (primarily dRDF) from the hand sorts was weighed with the pellets. The consistency of the weight percentage of the samples evidenced the repeatability and homogeneity of the coal:dRDF blending. The relative standard deviation of the pellet fraction was less than 5 percent in these samples. Table 2 summarizes the sampling results.

TABLE 2. PERCENTAGE OF PELLETS IN HAND-SORTED SAMPLES

	Blend	Time of Sample	% Pellets (by weight)
9 May	1:1	10:15	0.54
	1:1	11:30	0.46
	1:1	12:50	0.44
	1:1	2:00	0.47
	1:1	3:15	0.53
10 May	1:2	9:15	0.66
	1:2	10:10	0.63
	1:2	12:30	0.65
	1:2	1:35	0.62
	1:2	-	0.64

Alternative Fuel Blending Method

Although the fuel blending and handling system functioned as designed, some preliminary tests had to be performed before the drives on the Z-belt conveyors could be set at the proper speed ratios. For these initial tests, the operator of the front-end loader alternately loaded coal and dRDF into the feed hopper of the bucket elevator. When the hopper was full, the bucket elevator was started, and the gate to the feed chute was opened. The layered fuel flowed satisfactorily from the hopper. Moreover, samples of the blend taken from the weigh lorry were consistently mixed.

Consequently, the alternate coal and dRDF layering may be considered as effective in blending the two fuels as the proportioning conveyor mixing system.

Summary

Except for flow problems experienced with deteriorated pellets, the field tests demonstrated that conventional equipment can adequately blend coal and dRDF in various coal:dRDF ratios and can handle both the coal-only and the blended fuel. Such equipment, however, may require provisions to suppress dusting at conveyor transfer points.

SECTION 4

BOILER PERFORMANCE

BOILER DESCRIPTION

The MCI boiler plant in Hagerstown consists of three 1034-kPa (150-psig) Erie City Iron Works boilers. Their design steam ratings are 9.9, 7.6, and 3.2 kg/sec (78,500, 60,000, and 25,000 lb/hr). Figure 9 shows a cross section of a typical boiler. Each unit is equipped with a Hoffman Combustion Engineering "Firerite" spreader-feeder with an appropriate number of spreader-feeders to distribute the lump fuel in the furnace. The large coal pieces that do not burn in suspension are consumed on the surface of the front ash discharge vibrating grates.

The Erie City Iron Works boilers have tube-and-tile furnaces. The waterwalls are composed of nominal 8.26-cm (3 1/4-in.) diameter tubes that are partially covered by refractory to approximately 2.4 m (8 ft) above the grate surface. The gases exit from the furnace passing through a two-drum, vertically baffled boiler bank consisting of rows of in-line 5.7-cm (2 1/4-in.) diameter tubes arranged in two gas passes. The boiler unit flue gases pass through a decantation two-stage multiclone collector. The fly ash captured in the first-stage collector is injected into the furnace to complete combustion of the fly char, and the fly ash in the second-stage collector is pneumatically transported to disposal. The cleaned gases are induced through a centrifugal fan and exhausted to a breeching (common to all boilers) and then to the stack.

BOILER CONDITIONS

Before testing the boilers, all the associated instruments, such as the steam flow meters and the pressure and temperature gauges, were calibrated by Johnson Controls. The boiler settings, grates, and grate seals were visually inspected to determine their general condition and to seal obvious leaks. Refractory cement was applied at various locations on the boiler setting to seal leaks. In addition, the spreaders were adjusted for proper distribution on MCI normal coal.

Most of the December through March tests were performed in Boiler No. 1, the 9.9 kg/sec (78,500 lb/hr) boiler. Boiler No. 2 was not used for the initial testing because it was the only boiler equipped with both electric and steam-driven facilities and had the capability of cold starting. Consequently, most of the preparatory effort was devoted to putting Boiler No. 1 in good operating condition. However, the automatic control systems for

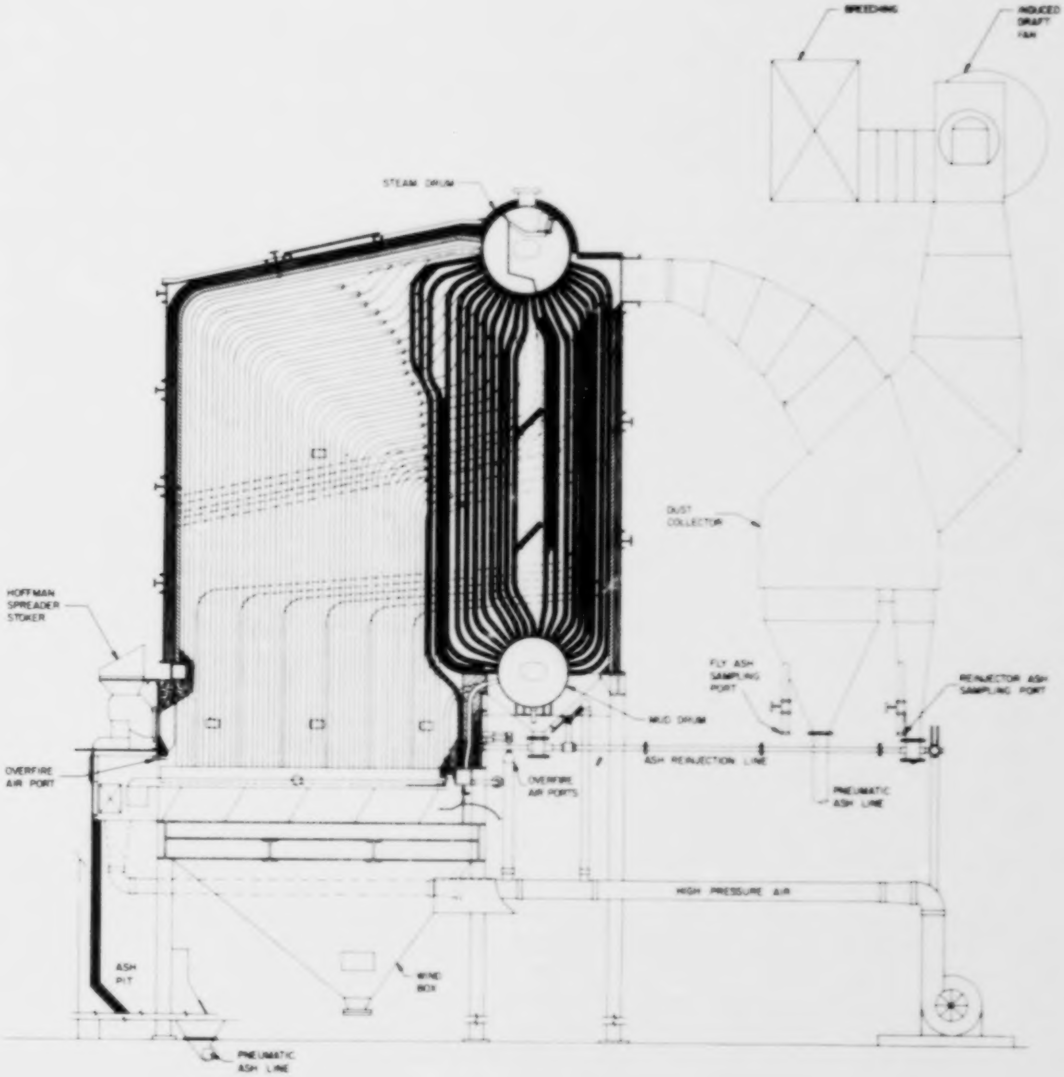
BREECHING
INDUCED DRAFT FAN
STEAM DRUM
DUST COLLECTOR
HOFFMAN SPREADER STOKER
FLY ASH SAMPLING PORT
REINJECTOR ASH SAMPLING PORT
MUD DRUM
OVERFIRE AIR PORT
ASH REINJECTION LINE
OVERFIRE AIR PORTS
PNEUMATIC ASH LINE
HIGH PRESSURE AIR
ASH PIT
WIND BOX
PNEUMATIC ASH LINE

Figure 9. Cross section of Boiler No. 2.

Boiler No. 1 were in such poor condition that the boiler had to be operated in the manual mode much of the time. The boiler tubes, grate, and refractory were in generally good condition, but there was some grate seal leakage.

Since the restriction on Boiler No. 2 was eventually lifted and because tests had to be scheduled according to the extremely limited availability of an EPA mobile electrostatic precipitator which could be tied into only one boiler, Boiler No. 2 was selected for the May tests.

During the start-up of the May test, air leakage around the grate seals produced air levels higher than those normally existing in boilers of this type. The leakage was detected when Orsat analyses were performed on combustion gases sampled at various cross-sectional scans and heights above the grate.

The following two sections on the boiler performance when substituting dRDF for coal are as follows: the first examines the properties of the coal and dRDF and their blends, and the second covers how the fuels responded in the boiler subsystems.

FUEL PROPERTIES

The following discussion on the properties of coal, dRDF, and coal:dRDF blends is preparatory to discussing their handling and burning in the field test program.

Coal Properties

The coal used during the four field tests (December, January, March, and May) came from different mines. This variation in the coal supply was the result of the procurement procedures of the State of Maryland and the need to use a specification coal during actual test runs.

During December the plant burned a coal which had a low ash fusion temperature, high heating value, and 3 percent sulfur. In January, the coal (supplied from the Pittsburg/Swickley seam) had a high ash fusion temperature. However, the fines were excessive with 85 percent passing a 6.3-mm (1/4-in.) sieve. In March and May, the coal met the ash fusion, heating value, and size constraints of the stoker manufacturer. Laboratory analyses of the coal samples taken throughout the test program are presented in Table 3. Examination of these coal properties reveals that the coal burned in March was different from that fired in May.

During each daily test 2.2- to 4.5-kg (5- to 10-lb) coal samples were taken periodically for subsequent analysis. At the end of the day the samples were mixed, and the composite was divided by sectioning. The final samples were placed in two separate containers for shipment to laboratories. First, a 300- to 500-gram sample was placed in a 1/2-liter rigid polyethlyne jar with a vapor proof lid and sealed. This sample was sent to the SYSTECH laboratories for moisture determinations. Second, samples were placed in 4-mil polyethylene bags and taped shut. Subsamples from these macro samples were sent to Broeman Laboratories and Commercial Testing and Engineering

TABLE 3. AVERAGE PROPERTIES OF COAL ON BOTH AN AS-RECEIVED AND A MOISTURE-FREE AND ASH-FREE BASIS

	December Average	January Average	March Average	May Average	December Average	January Average	March Average	May Average
As Received								
% Moisture	2.12	7.03	3.78	1.27	COAL MOISTURE AND ASH FREE			
% Ash	10.78	14.30	10.23	21.95				
% Volatile	29.42	16.16	22.43	22.55	33.78	20.60	26.14	29.13
% Fixed Carbon	57.68	62.50	63.55	54.23	66.22	79.40	73.84	70.87
Btu/lb	13,471	11,797	12,959	11,706				
MJ/kg	31.33	27.44	30.14	27.23				
Dry Basis								
% C	77.15	70.50	74.15	67.40	86.70	83.34	82.98	86.73
% H	4.77	3.80	4.38	4.33	5.36	4.49	4.90	5.56
% N_2	1.26	1.57	1.59	1.35	1.42	1.85	1.77	1.72
% Cl	.26	---	.11	.05	.29	---	.13	.07
% S	3.57	1.80	1.72	1.22	4.01	2.12	1.93	1.43
% Ash	11.01	15.40	10.63	22.23				
% O_2	1.98	6.93	7.42	3.42	2.23	8.19	8.38	4.35
Btu/lb					15,446	14,996	15,069	15,246
MJ/kg					35.93	34.88	35.05	35.46
Fusion								
Initial	1128°C	1332°C	1274°C	1482+°C				
1st Softening	1192°C	1368°C	1308°C	1482+°C				
2nd Softening	1249°C	1379°C	1335°C	1482+°C				
Fluid	1371°C	1414°C	1371°C	1482+°C				
Mineral Analysis								
Phos. Pent Ox.	.48	.92	.41	.33				
Silica	35.43	43.50	52.02	59.62				
Ferric Ox.	34.94	21.00	12.74	5.80				
Alumina	22.39	20.70	25.64	27.43				
Titania	.56	1.42	.70	.90				
Sodium Ox.	.25	2.70	.47	.31				
Potasium Ox.	.99	2.37	1.87	2.32				
Lime	1.63	.38	2.18	.54				
Magnesia	.28	.58	.36	1.15				
Sulfur Tri Ox.	1.23	.83	1.66	.32				
Undetermined	1.82	---	1.95	1.32				

NOTE: Hemispheric (Second Softening) temperatures in excess of 1204°C (2200°F) are preferred.

Corporation for fuel property analyses. These analyses included standard ASTM ultimate and proximate determinations, ash chemistries, and reducing atmosphere fusion temperatures. The analyses were ultimately expanded to include a determination of chlorine. Table 3 lists the averages of the test coal properties. The individual determinations from which the averages were derived are contained in Appendix A.

Part of each macro sample was sized by using a Tyler portable sieve shaker and a standard set of ASTM coal-sizing sieves. The sieves used were nominal 1-, 3/4-, 1/2-, 3/8-, and 1/4-inch screens. Figure 10 shows the size distributions of the coal samples overlayed on a probability display of the recommended spreader stoker coal distribution.

The bulk density of the coal was determined by loosely filling a 0.03-m^3 (1-ft^3) container with coal, without its being agitated or tamped, and by weighing the container on a 100-lb capacity platform scale. The bulk

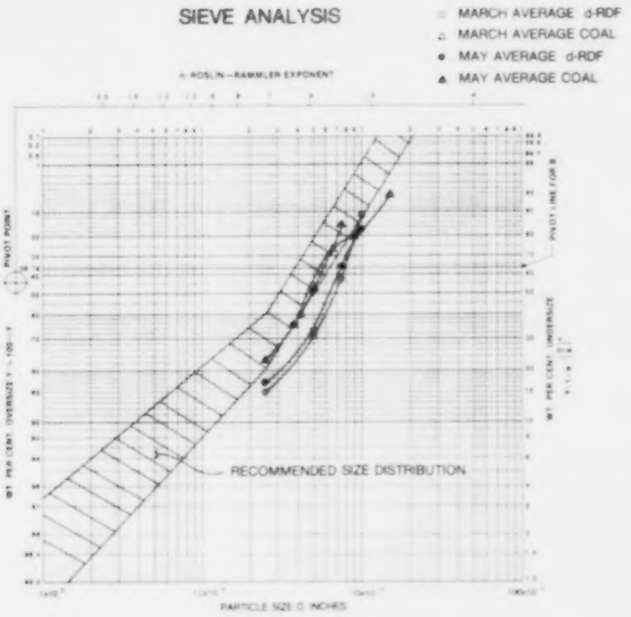

Figure 10. Coal and dRDF size distributions compared with recommended size spectra.

density was determined by dividing the weight of the material by the volume of the container. The density of the coal particles was determined by weighing lumps of coal; measuring the amount of liquid displaced by each piece when it was immersed in a water-filled, 500-mℓ, graduated cylinder; and dividing the piece weight by the total volume of coal.

Because the use of a fuel may be limited by its heat density (the amount of energy per unit volume), the amount of air required to burn the fuel, or the ability to introduce the fuel into the furnace, there is a particular interest in the heat density (MJ/m^3) of the fuel and the theoretical mass (kg) of air required to burn a unit mass (kg) or unit energy value (MJ) of fuel. The data obtained from the laboratory analyses of the fuel were substituted in Equation 4.1 to determine the theoretical air requirements:

$$TA = 11.53C + 34.34(H_2 - O_2/8) + 4.29S \quad kg_{air}/kg_{fuel} \qquad (4.1)$$

where C, H, O, and S are the respective weight fractions of the element in the fuel ultimate analysis.

The air requirement can also be expressed in terms of the mass per heat content equivalent of fuel by using the available fuel properties information:

$$\mathrm{kg_{air}/MJ} = \frac{(\mathrm{kg_{fuel}/kg_{air}}) \times 10^6}{\mathrm{J/kg_{fuel}}} \qquad (4.2)$$

The volumetric heat rate (megajoules per cubic meter) is the parameter which determines the amount of energy that the volumetric feeders can introduce into the furnace. This parameter is particularly important in a retrofit application to determine the maximum amounts of dRDF which can be substituted for coal and still have sufficient feeder capacity.

$$\mathrm{MJ/m^3} = \frac{\mathrm{J/kg \times kg/m^3}}{10^6} \text{ (bulk density of fuel)} \qquad (4.3)$$

dRDF Properties

Procedures similar to those for the coal sampling were used to collect dRDF samples. Each time the dRDF was sampled, one sample was sealed to permit moisture determination at the SYSTECH laboratories and another was immediately processed for size and composition.

Table 4 lists the averages of the dRDF properties including ultimate and proximate analyses, chlorine, reducing atmosphere ash fusion temperatures, and ash chemistries. The table also includes the same information recalculated on a moisture-free and an ash-free basis. The individual determinations from which the averages were derived are contained in Appendix A.

The theoretical air requirements (expressed as kilograms of air per megajoule) and the volumetric heat rate (megajoules per cubic meter) were computed by substituting the laboratory data in Equations 4.1 through 4.3.

Blend Properties

The theoretical combustion properties of coal:dRDF blends can be mathematically computed once the heating value, the bulk density, the mass, and the heat or volumetric blend ratio of the components are known.

Throughout the current study the mixture of coal and dRDF was given a volumetric ratio designation. For example, a 1:1 blend would be an admixture of 1 m^3 of coal with 1 m^3 of dRDF.

It is important, also, to know both the weight and the heat mixture of the blended fuels in order to compare the test results with predictions made by others as well as to size the fuel handling system, to estimate the ash handling requirements, and to determine the best feed rate of blended fuel entering the boiler.

TABLE 4. AVERAGE PROPERTIES OF dRDF ON BOTH AN AS-RECEIVED AND A MOISTURE-FREE AND ASH-FREE BASIS

	December Average	March Average	May Average	December Average	March Average	May Average
As Received						
% Moisture	13.40	12.62	12.22	dRDF MOISTURE AND ASH FREE		
% Ash	19.97	24.41	28.75			
% Volatile	56.54	54.08	49.27	85.04	85.80	83.38
% Fixed Carbon	10.10	8.89	9.76	14.97	14.21	16.62
Btu/lb	6488	5534	5266			
MJ/kg	15.09	12.87	12.25			
Dry Basis						
% C	43.98	39.17	35.63	54.29	54.42	53.36
% H	5.29	4.47	4.54	6.53	6.20	6.75
% N_2	.35	.39	.85	.43	.54	1.25
% Cl	.40	.45	.36	.49	.62	.54
% S	.40	.26	.28	.53	.36	.42
% Ash	23.19	27.97	33.02			
% O_2	30.80	27.30	25.33	38.02	37.87	37.68
Btu/lb				9785	8772	8956
MJ/kg				22.76	20.40	20.83
Fusion						
Initial	1103°C	1116°C	1096°C			
1st Softening	1142°C	1151°C	1152°C			
2nd Softening	1191°C	1179°C	1163°C			
Fluid	1246°C	1213°C	1218°C			
Mineral Analysis						
Phos. Pent. Ox.	.87	.73	.65			
Silica	55.52	71.58	63.65			
Ferric Ox.	2.27	2.89	2.64			
Alumina	13.45	4.43	8.39			
Titania	.66	.99	.69			
Sodium Ox.	6.82	5.66	7.53			
Potasium Ox.	1.30	.53	.91			
Lime	10.75	7.50	9.74			
Magnesium	1.14	1.12	1.59			
Sulfur Tri. Ox.	6.03	1.22	3.20			
Undetermined	1.19	1.87	1.00			

NOTE: Hemispheric (Second Softening) temperatures in excess of 1204°C (2200°F) are preferred.

The properties of the fuel for the various blends used in March and May are listed in Tables 5 and 6.

The weight fraction of dRDF determined by physically separating the coal from the dRDF and weighing each component had a relative standard deviation of less than 5 percent. Hence, the blending system was producing a uniform blend. The hand-sorted weight ratios are consistently higher than the calculated weight ratios, probably because all fines not identified as coal were considered dRDF. Since the coal contained between 15 and 30 percent fines, the dRDF fraction was biased by considering all unidentified fines as dRDF.

It would normally be expected that a linear interpolation should be applicable for blends when the density of coal and the density of dRDF on a volumetric basis are used to determine the relative density of the two fuels. The fact that the fuel densities are uniformly higher than the interpolated densities is understandable when both coal and dRDF are considered as ensembles of solid particles which have different void sizes. When two solid fuels are admixed, the relative void between the two fuels frequently becomes smaller because some of the coal particles will fill voids in the dRDF and some of the dRDF particles will fill voids in the coal structure. Consequently, the bulk density of an admixture would likely be higher than the density determined by straight interpolation. This error, however, is small and was determined to be less than 3 percent for all blends.

Conclusions

In the current tests, the substitution of dRDF for coal increased the ash and decreased the volumetric heat density of the blend. However, the air:fuel ratio (kilograms air per megajoule equivalent) actually declined as dRDF was substituted for coal. If the coal:dRDF blends can be fired at the same excess air level as coal alone, the forced and induced draft fans should be adequate, assuming there is little efficiency deterioration. The decrease in heat content for a given fuel volume could cause the furnace fuel feeders to become limiting. Increases in ash content could overload ash handling equipment or air pollution control equipment.

FUEL HANDLING AND RESPONSE IN BOILER SYSTEMS

The three boilers at the Hagerstown plant are similar in configuration although different in capacity. Each boiler can be divided into five subsystems: fuel feeding distribution, furnace, controls, air and gas handling, and ash handling. The fuel distribution system moves the fuel from outside the boiler into the furnace where it is combusted and converted to heat energy and ash. The ash handling system removes the solid residue from the furnace and air pollution control equipment. The air and gas handling system moves air to the furnace for combustion, draws the combustion products through the heat transfer sections, and exhausts the gases to the atmosphere. The furnace and boiler system removes heat from the combustion products and converts it into steam. The control system coordinates the activities of the fuel and air handling systems in response to energy requirements of the furnace system as coupled with plant demand.

TABLE 5. AS-FIRED PROPERTIES FOR BLENDS IN MARCH TESTS*

	AS FIRED			
VOLUMETRIC BLEND	1:0	1:1	1:2	0:1
PARAMETER				
Btu/#	12714	9180	8706	6034
MJ/kg	29.5	21.3	20.2	14.0
Moisture	4.9	7.4	7.7	9.6
Volatiles	30.4	44.9	46.8	57.8
Fixed Carbon	54.2	29.8	26.5	8.1
Ash	10.5	17.9	18.9	24.5
C	71.5	51.3	48.6	33.4
H	4.7	4.6	4.6	4.5
N	1.3	.8	.8	.4
O	5.6	16.8	18.3	26.8
S	1.5	.8	.7	.2
Cl	.06	.24	.3	.4
%dRDF				
by Volume	0	50	67	100
by Weight	0	35	52	100
by Heat	0	20	36	100

*Unless noted, all values are weight percent on a wet basis.

TABLE 6. AS-FIRED PROPERTIES FOR BLENDS IN MAY TESTS*

	AS FIRED			
VOLUMETRIC BLEND	1:0	1:1	1:2	0:1
PARAMETER				
Moisture*	1:3	6.6	7.9	16.6
Volatiles	22.6	31.7	38.3	48.6
Fixed Carbon	54.2	38.4	29.1	9.0
Ash	22.0	23.2	24.7	25.9
Btu/lb	11706	8988	8382	5130
MJ/kg	27.2	20.9	19.5	11.9
Carbon	66.5	54.1	47.3	30.9
Hydrogen	4.3	4.1	4.1	3.8
Oxygen	3.4	9.8	14.2	21.8
Nitrogen	1.3	1.1	.9	.6
Sulfur	1.2	.86	.66	.23
Chlorine	.05	.15	.21	.33
FUSION TEMP. -C				
Init. Def.	1274			1116
1st Soft.	1308			1151
2nd Soft.	1335			1179
Fluid	1371			1213
THEORETICAL AIR				
kg/kg fuel	9.04	7.26	6.27	3.93
kg/MJ in fuel	.351	.347	.332	.331
% Weight Rate dRFD	0	35	52	100
% Heat Rate dRFD	0	20	37	100

*Unless otherwise noted, all values are weight percent on a wet basis

Fuel Distribution

System Description--

Each of the three boilers is equipped with Hoffman Combustion Engineering Type A "Firerite" underthrow spreader-feeders. Figure 11 is a cross section of a typical spreader-feeder mounted on the stoker front plate of the boiler. The solid fuel is placed in the coal hopper and flows by gravity to a reciprocating feed plate which advances the lump fuel over the distributor blades. As the reciprocating feed plate moves forward, the lump fuel falls into the rotor and is carried between the rotor and the rotor casing through 220 degrees of arc before being thrown into the furnace.

Adjustments on the spreader include varying the rotor speed to change the length of the particle trajectory and varying the position of the rotor casing (circular tray) to alter the arc of the particle trajectory. Slowing the rotor shortens the particle throw. When the rotor casing is moved forward (toward the furnace), the fuel particles are thrown into a higher trajectory. Although the two adjustments jointly determine the longitudinal fuel pattern, rotor speeds are adjusted grossly while the casings are adjusted finely so that the fuel introduced by each spreader-feeder lands at approximately the same distance from the back furnace wall.

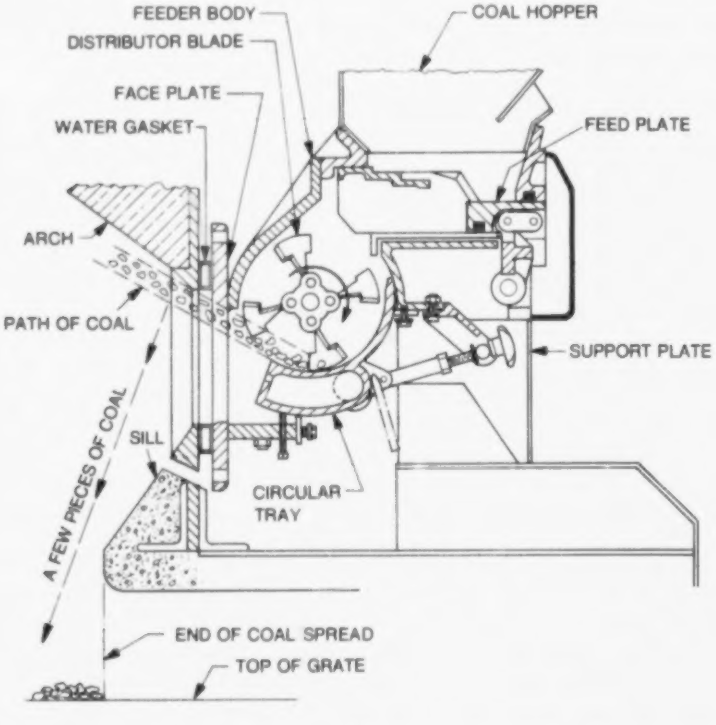
FEEDER BODY
DISTRIBUTOR BLADE
FACE PLATE
WATER GASKET
ARCH
PATH OF COAL
SILL
A FEW PIECES OF COAL
CIRCULAR TRAY
COAL HOPPER
FEED PLATE
SUPPORT PLATE
END OF COAL SPREAD
TOP OF GRATE

Figure 11. Cross section of Hoffman Combustion Engineering spreader-feeder.

Cold Flow Test--

The cold flow test (feeding fuel to an idle boiler with no fire) was designed to demonstrate that coal:dRDF blends could be successfully handled and distributed into the furnace. The first goal of the cold flow test was to operate and verify the performance of the new fuel conveying system that had been installed to bypass the existing coal silo. This system conveyed dRDF and coal:dRDF blends into the coal weigh lorry which in turn supplied the stoker coal hoppers of the three boilers. Initially the operation of the conveyor system was unacceptable because the coal and pellet conveyors ran too slowly. Subsequently this problem was easily corrected.

To test the ability to feed pellets, two basic pellet sizes were fed into the furnace: nominal 1-inch-diameter by 2-inch-length pellets were used for the first experiment, and nominal 1/2-inch-diameter by 3/4-inch-length pellets were used for the second. In each experiment the test sample was 44 kg (97 lb). In the first experiment, with the reciprocating feed plate adjusted for maximum stroke, 4 1/2 minutes were required to feed the nominal 1-inch-diameter by 2-inch-length pellets, an an average rate of about 9.7 kg/min (21.3 lb/min). During this experiment unusual feeder noise indicated some pellet breakage was occurring. The noise was attributed primarily to the rotor casing (circular tray) clearance limitations. Although there were no difficulties during this test, it was concluded that if the 1-inch-diameter by 2-inch-length pellets were simultaneously fed to all four stoker spreader-feeders (which are driven by a single motor and drive shaft), they could cause shear pin failure.

In the second experiment, with the feeder adjustment similar to that used during normal coal firing, the 1/2-inch-diameter by 3/4-inch-length pellets were fed into the furnace in about 3 minutes, an average rate of about 11.3 kg/min (25 lb/min). During this experiment no unusual noise or other events were noted.

In both cold flow experiments the fuel distribution patterns (both lateral and longitudinal) were excellent, and the pellets were generally fed to the desired furnace locations. Figure 12 shows fuel being fed through the spreader. Fine material accumulated at the bottom of the spreader opening because the feed fan air jet was turned off during the test to minimize dusting inside the boiler. Figure 13 shows coal and pellets spread on top of each other with the fuels rather uniformly dispersed. The spreader performed as intended in that the larger pellets with the greater mass traveled to the rear of the furnace with the fines falling closer to the spreader.

The area densities of the 1/2-inch-diameter by 3/4-inch-length pellets spread into the furnace were determined as follows: A rough square of the fuel on the grate was isolated with a flat shovel; see Figure 14. The isolated pile of fuel was then collected and weighed. The average density across the grate section was determined by dividing the weight of the collected pellets by the area covered by the pile. For each of four distances from the back wall, Table 7 lists the spread density and condition of the pellets.

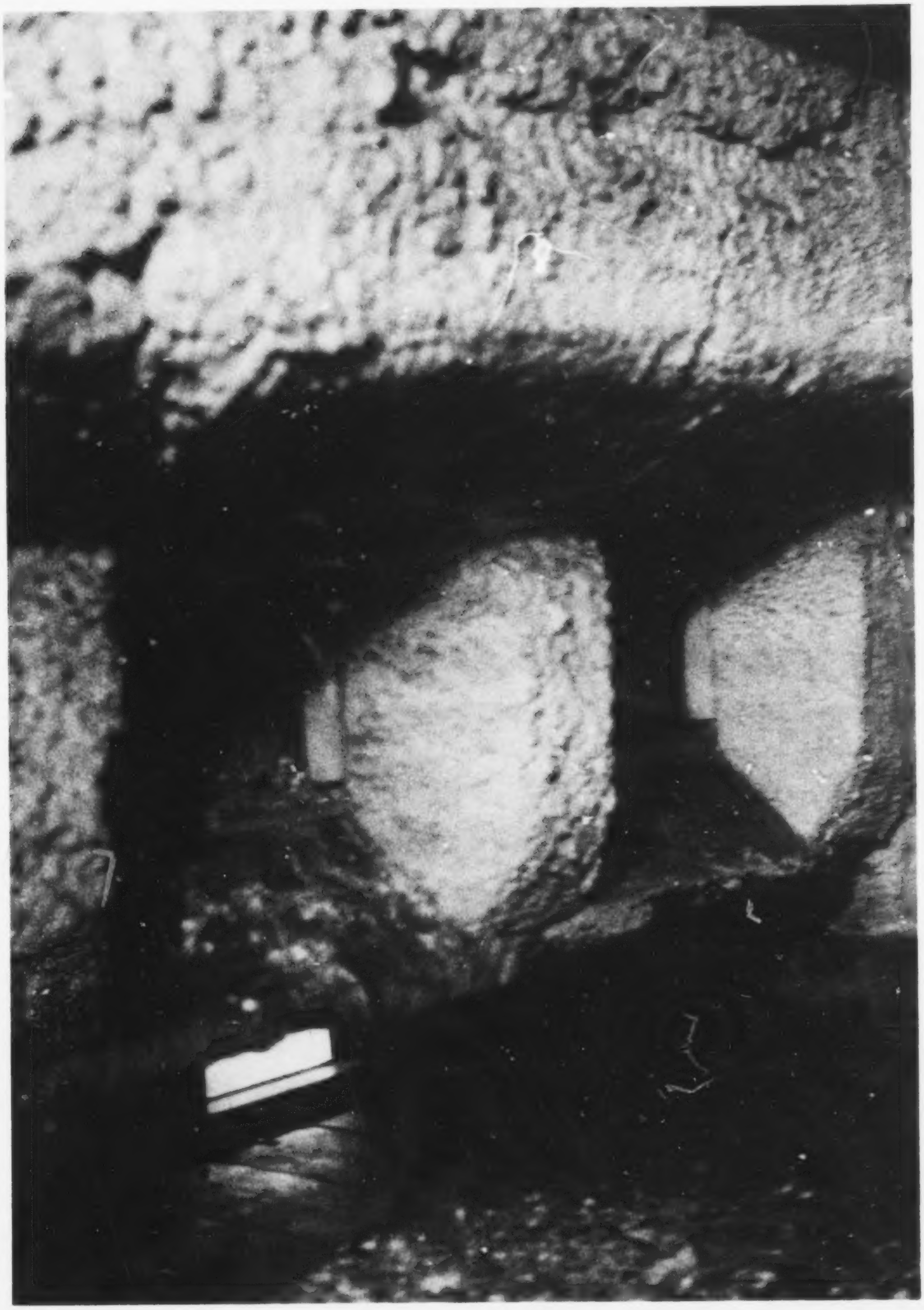

Figure 12. Spreader-feeder injecting a dRDF:coal blend into furnace.

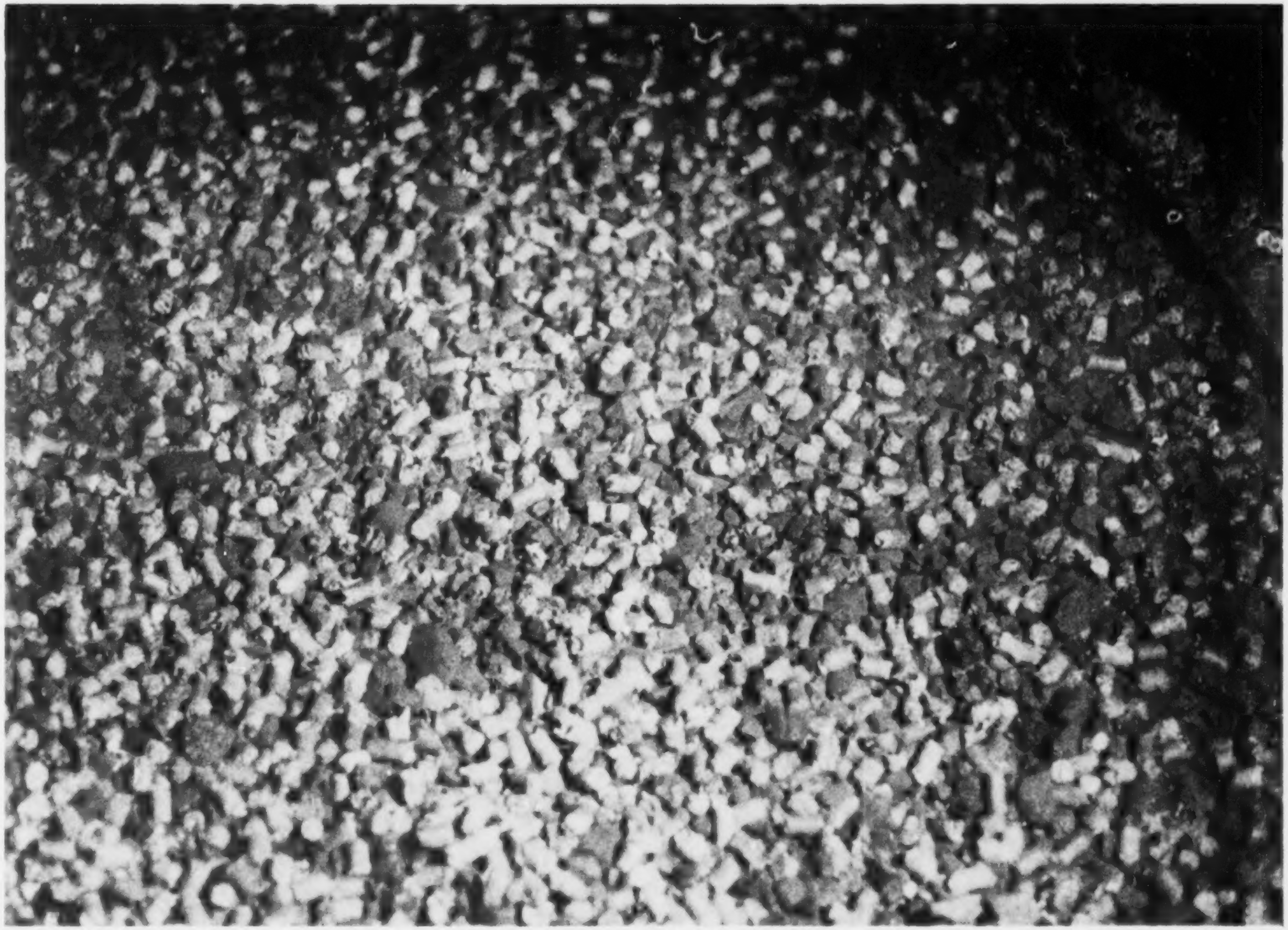

Figure 13. Uniform distribution of coal and dRDF pellets near the furnace rear wall.

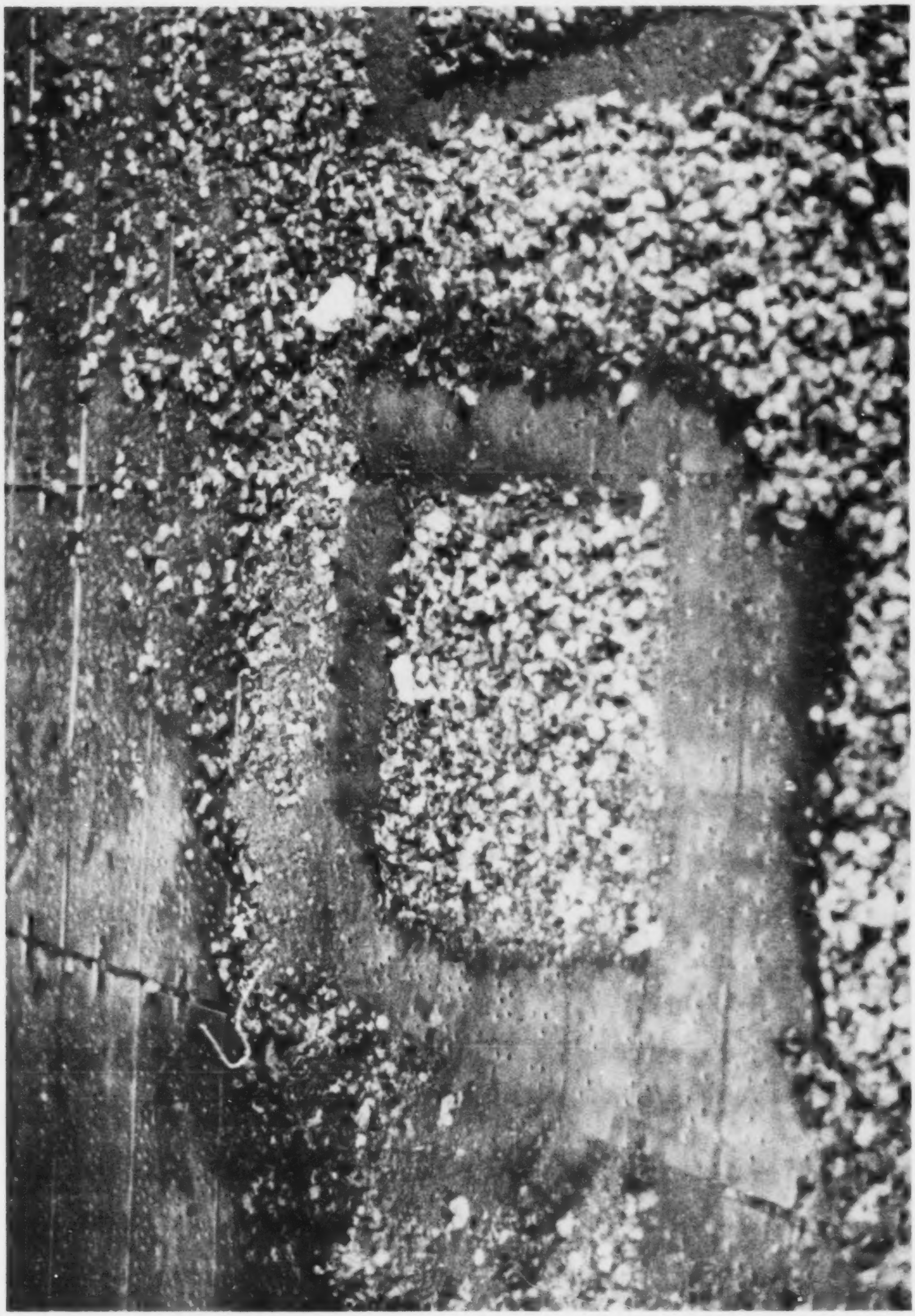

Figure 14. Isolation of grate dRDF to determine its spread density.

TABLE 7. AREA DENSITY OF PELLETS REMOVED FROM THE COLD FLOW TEST

Distance (m) from back wall	Spread density (kg/m^2)	Pellet Condition
1.07 (42 inches)	29.5 (6.06 lb/ft^2)	whole
1.52 (60 inches)	12.9 (2.65 lb/ft^2)	whole
1.83 (72 inches)	12.0 (2.46 lb/ft^2)	whole
2.90 (114 inches)	21.3 (4.35 lb/ft^2)	large number of fines

The cold flow test indicated that the 1/2-inch-diameter by 3/4-inch-length pellets produced a spread density which was high near the front and rear walls and low in the middle of the grate. Approximately twice as much fuel was located at the rear wall than in the middle of the grate. Subsequent testing during the hot flow test confirmed that the pellet throw was too long.

Hot Flow Test--

It was decided to fire 100 percent pellets for a short period of time to determine their impact on furnace performance. A total of 945.7 kg (2085 lb) of 1/2-inch-diameter dRDF pellets were weighed in the lorry. When the stoker coal hopper of the No. 2 boiler was empty, the pellets in the lorry were discharged into the hopper. The steam pressure was 1055 kPa (153 psi), and the steam flow was about 3.8 kg/sec (30,000 lb/hr). The cam on each of the Hoffman spreader-feeders was adjusted to the maximum feed stoke. The spreader rotor rpm was 60, the same as that used for coal. After the pellets were fed into the furnace, it was immediately obvious that the fuel trajectory was too long, causing fuel and flame to impinge on the rear furnace wall. The trajectory was reduced some 0.3 m (12 in.) by slightly retracting the circular tray. Fifteen minutes after starting the pellet feed, the steam pressure had decreased to 1027 kPa (149 psi). This pressure generally prevailed for the remaining 5 to 7 minutes of the test. The pressure had dropped because the spreader-feeders were incapable of supplying a sufficient quantity of fuel to the furnace to maintain the steam pressure. The average firing rate for the three feeders collectively was 48 kg/min (105 lb/min) or about 15.9 kg/min (35 lb/min) for each feeder. While the steam pressure decreased during the 20-minute firing with a 0:1 blend, the steam flow remained about 3.8 kg/sec (30,000 lb/hr) which was 50 percent of boiler rating. This dropping steam pressure indicated that the boiler system could not carry the 50 percent load when firing 100 percent pellets.

Following the successful 0:1 test, a 1:1 blend test was fired. During this test there was frequent clinkering on the grate. One cause of this clinkering is that when a fuel with too low an ash fusion temperature is placed on the grate and agitated, hot burning particles with molten edges roll against and under each other as the grate is vibrated. The burning particles, which are now within the ash bed, heat the ash so that the softened ash sticks together, restricting cooling air flow, and begins to form a skin clinker layer across the bed surface. This skin clinker becomes progressively less permeable than the open portions of the ash and fuel bed; consequently, less air is supplied to the fuel/ash bed prompting progressively deeper clinkering. As new fuel is fed into the furnace and falls on top of the skin clinker, the airflow is retarded still more, and the clinkering condition is further aggravated, and smoking becomes severe.

The ash fusion temperature analysis of the coal revealed that the hemispheric reducing ash fusion temperature was 1191°C (2176°F). Since reducing hemispheric ash fusion temperatures in excess of 1204°C (2200°F) is preferred for proper combustion conditions, it is not surprising that clinkering was encountered. Since continuation of this clinkering during blend firing would not permit evaluation of the effect of pellets, a different coal had to be procured for subsequent tests.

Even though the pellets have an ash fusion temperature less than that of coal, the furnace operated satisfactorily when the 100 percent pellets were burned. Assuming that the ASME definition for lignitic type ash (defined as ash in which the sum of CaO + MgO is greater than Fe_2O_3)[1] applies to dRDF ash (which has a CaO + MgO to Fe_2O_3 ratio of 4), then dRDF burns similarly as a lignite coal. Therefore the boiler design rules for lignite, rather than those for bituminous coal, more nearly apply when burning dRDF.

During January the testing switched from Boiler No. 2, which is a 7.6 kg/sec (60,000-lb/hr) boiler with three spreader-feeders, to Boiler No. 1, which is a 9.9 kg/sec (78,500-lb/hr) boiler equipped with four spreader-feeders. In the January tests the boiler was fired with a 1:1 blend for 4 hours and with 100 percent pellets for 2 hours. During the 1:1 firing, the overfire air and fly ash reinjection air pressures were adjusted to produce the desired flame mixing and low smoke opacity. Further discussion on these adjustments are provided later in the text. The stack plume was relatively clear during both the 1:1 and 0:1 blend firings. While firing with the 1:1 blend, there was no reoccurrence of the clinkering which was experienced during the December tests. This improved performance was due to the coal having a hemispheric fusion temperature of about 1373°C (2500°F). The December coal fusion temperature was 1204°C (2200°F).

When the blend ratio was changed to 100 percent dRDF, the furnace remained clear of smoke streamers for the first 20 to 30 minutes of firing, and there was no significant smoking. Subsequently two rows of ash were observed on the fuel bed in line with the fly carbon reinjection nozzles. Figure 15 shows the location of three of the fly carbon reinjection nozzles at the back of the furnace. Each of the two rows was in line with the double fly ash reinjection ports (one reinjector for the dust caught in the boiler bank passes, the other for the coarse stage multiclone). This ash layer phenomenon might be alleviated by spacing the fly ash reinjection nozzles more uniformly across the rear wall of the furnace or increasing the number of reinjection lines. The reinjection ash rows moved well through the furnace

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[1] Winegartner, E. C. Coal Fouling and Slagging Parameters. American Society of Mechanical Engineers, 1974.

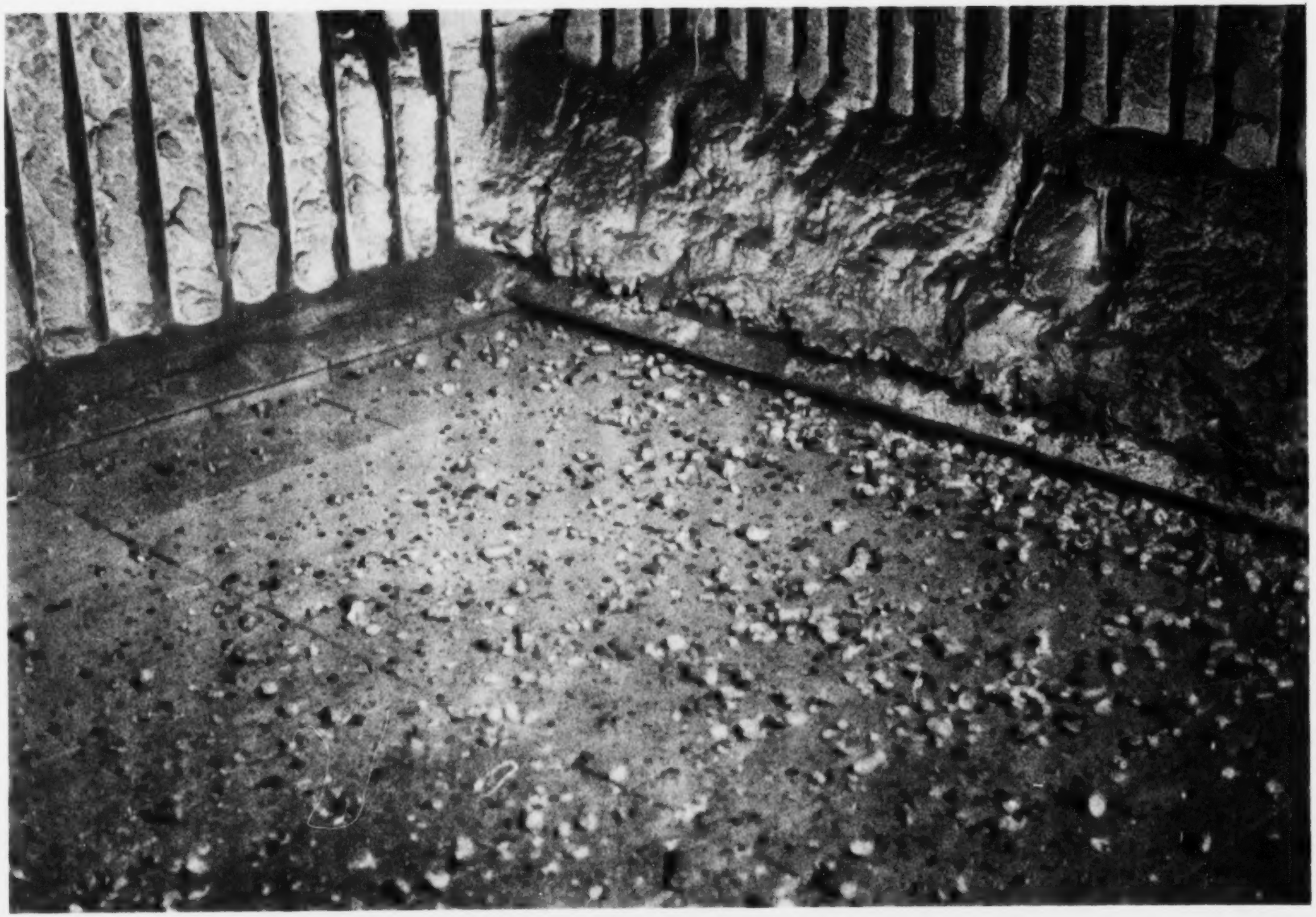

Figure 15. Ash reinjection and overfire air ports in rear wall of Boiler No. 1.

as the grate vibrated, and they remained sufficiently porous for airflow. There was also a base of burned-out ash under the ash rows.

The furnace volume appeared more than adequate for the combustion taking place, although a maximum of 6.8 kg/sec (54,000 lb/hr) of steam could be generated when firing 100 percent pellets. This unmodified vibrating-grate, stoker-fired boiler supported 70 percent of the nominal rating for 2 hours when firing 100 percent pellets. The magnitude of this derating is the amount predicted by the volumetric limitations of 1.47 m^3/hr (52 ft^3/hr) for the feeder. The forced draft fan capacity was sufficient to meet the underfire air requirements at this rating.

When a 1:1 blend was fired, there was no difficulty in maintaining the 1034 kPa (150 psig) boiler steam pressure. However, when 100 percent pellets were introduced, the steam pressure fell to about 1000 kPa (145 psig) while supplying 6.8 kg/sec (54,000 lb/hr) steam flow. This pressure drop was due to volumetric feeding limitations of the spreader-feeders. After the initial loss in pressure, the boiler operated at this reduced pressure for the rest of the test.

The principal change required during the 1:1 and 0:1 blend tests was to reduce the spreader rotor speed so that the throw of the pellets would be approximately 0.15 m (6 in.) less than that for 100 percent coal. This adjustment was necessary to prevent furnace rear wall fuel impingement.

During the combustion tests with 1:1 blend and 100 percent dRDF, the fireball was kept well away from the rear and front walls of the furnace by adjusting the overfire air. Once these jets were adjusted for minimum smoke and maximum turbulence efficiency for coal-only burning, they continued to meet the mixing and wall protection requirements when burning blends and 100 percent pellets. As viewed from the side of the furnace when firing both pellets and blends, the bed was well burned out by the time it approached the front ash pit. The flame pattern above the grate indicated that the fuel bed was maintaining proper porosity and that the combustion was good. With little attempt to optimize the system, a 10 to 12 percent carbon dioxide content in the flue gas at the boiler outlet was readily obtained.

Normal Boiler Operation--

The cold and hot flow tests showed that dRDF could be properly distributed into the furnace. The blend also had a distribution pattern on the furnace grate which was similar to that of coal. This finding is not particularly surprising since the size distributions and material densities (not bulk densities) of the coal and pellets were similar. Therefore, with the same velocity and angle of injection into the furnace, pellets and lumps of coal with equal weight would be expected to travel approximately the same distance.

There was a severe slag accumulation on the rear furnace wall in line with Spreader-feeder No. 1 during the May testing. To stop the slagging, the throw of all pellets was reduced approximately 15.24 cm (6 in.), and the circular tray in Spreader No. 1 was retracted slightly to reduce the arc of the pellet trajectories. After this adjustment the pellets still carried the same distance from the feeder and landed at the same place on the grate. However, the 15.24-cm (6-in.) throw reduction eliminated the slag accumulation on the furnace wall and reduced smoking. In December, January, and March, the material impinging on the side walls was not excessive. In May, however, Spreader No.1 had to be adjusted because of its throwing too far and spraying the left side wall of the furnace. Careful measurement of the spreader showed that the circular tray had skewed left. Once the tray was properly aligned, the fuel impingement on the left side wall was eliminated.

During January and March, Boiler No. 2 had a recurring problem of clinkering on the left side when burning coal. Reports received after the field testing stated that this clinkering had been eliminated by readjusting the spreader circular tray.

Proper adjustment of the spreader-feeders is critical to the successful combustion of coal:dRDF blends. During part of the March tests, clinkering on the grate in front of Spreader No. 2 recurred, but the rest of the fuel bed remained free burning. Clinkers formed on top of the piled burnt-out ash at the front and moved out of the furnace with some difficulty. The rear wall of the furnace remained clear of slag throughout these tests. During an unexpected furnace outage caused by a control loop failure (the dRDF in the furnace was not related to this failure), the furnace spreaders were inspected. While Spreaders No. 1, 3, and 4 were clear of pellets, Spreader No. 2 had a heavy accumulation of partially pyrolyzed pellets in the feed throat. Careful measurement of the tray position from the inside of the boiler indicated that the pellets were being thrown at too high an angle out of the spreader so that they ricocheted off the refractory feed throat and accumulated at a point in the furnace approximately two-thirds of the way back. This maladjustment was solved by retracting the circular tray approximately 3.18 mm (1/8 in.). The furnace was then brought back on line from a cold start with a 1:2 blend and run continuously at loads of 3.2 kg/sec to 4.2 kg/sec (25,000 to 33,000 lb/hr) for 48 hours with no further clinkering.

Ash Handling

System Description--

Each of the three boilers at the MCI plant is equipped with a dry pneumatic ash handling system. As the solid fuel burns on the vibrating grate, the grate is periodically pulsed to advance the ash to the front of the boiler where it falls into a refractory-lined ash pit. The bottom ash is manually hoed from the ash pit into the pneumatic ash handling system. After the ash is conveyed to a cyclone separator where it is de-entrained from the carrier air, it falls into an ash storage silo. The vacuum source for the pneumatic system is a steam ejector.

Ashes are also collected from under the boiler tube bank and from the particulate collectors. The ash from the tube tank and primary cyclone is reinjected into the furnace through nozzles in the rear of the furnace. The secondary multiclone collector ash is pneumatically transported to the de-entrainment cyclone and ash silo.

To discuss the findings on relative boiler ash flows when substituting dRDF for coal, the following aspects of the boiler ash handling system are addressed: grate, bottom ash, ash silo, and reinjection and collector fly-ash flows.

Grate --

As the fuel is spread into the furnace, portions of it burn in suspension, and the remainder falls to the grate. The primary combustion air is introduced into the furnace through the grate supporting the burning fuel and then into the furnace. The grate is maintained with a constant 5-cm (2-in.) ash covering by periodically vibrating it to advance the accumulated ash. In order to achieve a steady-state condition, as much ash must be removed as is added to the furnace with the fuel. The two principal means of control of the ash bed depth are the dwell period between grate pulses and the duration of the grate pulse. In addition to frequency, the amplitude of the agitation can also be adjusted to account for differences in ash bulk density.

Figure 16 shows the dwell between grate pulses for various blends as a function of boiler load. When the load increased, the frequency of pulses was increased to maintain the same depth of bed on the grate. Also, as the dRDF substitution ratio increased, the frequency and/or duration of pulse was increased to maintain the uniform bed depth. In all instances, pulse frequency was the principal controlling variable. The duration of pulse was adjusted to cause the fire line at the rear of the boiler to advance approximately 6 inches per excitation. The amplitude of the pulse was also adjusted to help clear the rear fire line from the furnace wall. Minimal adjustment to the amplitude was required. When firing a blend, the pulse duration tended to increase because the bulk density of blend bottom ash was less than that of the coal bottom ash. The outliers shown in Figure 16 were so indicated because the ash bed depth and fire line were not representative of normal boiler operation.

Bottom Ash--

As the ash was shaken from the grate into the ash pit, it was allowed to accumulate for approximately 8 hours. After this period the ash doors were opened, and the ash was hoed into the boiler's pneumatic ash handling system. When the grate was free of clinkers, the ash which accumulated in the hopper was free flowing and easily handled. Figure 17 shows the results of manual sieving of various bottom ash samples and indicates that the coal and dRDF ashes are equally well handled by a conventional pneumatic ash handling system.

Because the spreader paddles were worn, a significant amount of fuel "dribbled" onto the front of the grate and subsequently into the ash pit. Since this fuel had not ignited on the grate, mixing the unignited coal with the hot bottom ash often resulted in fires in the ash pit. When the ash pit had fire, the blend ash tended to be more plastic than coal-only ash and had a taffy-like consistency. The coal ash under similar conditions was much easier to break up.

The ash flow from the various blends was monitored by first cleaning the ash pit completely. Then, after the ash was allowed to accumulate in the pit

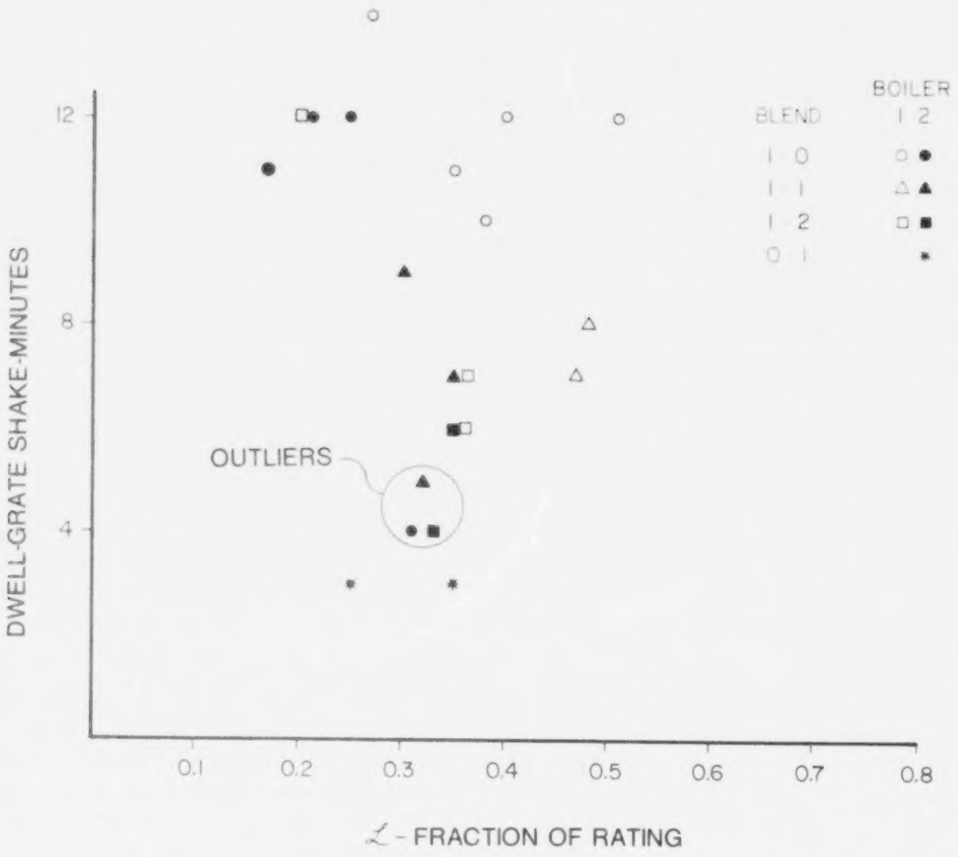

Figure 16. Effect of blend and load on grate pulse interval or relative grate speed.

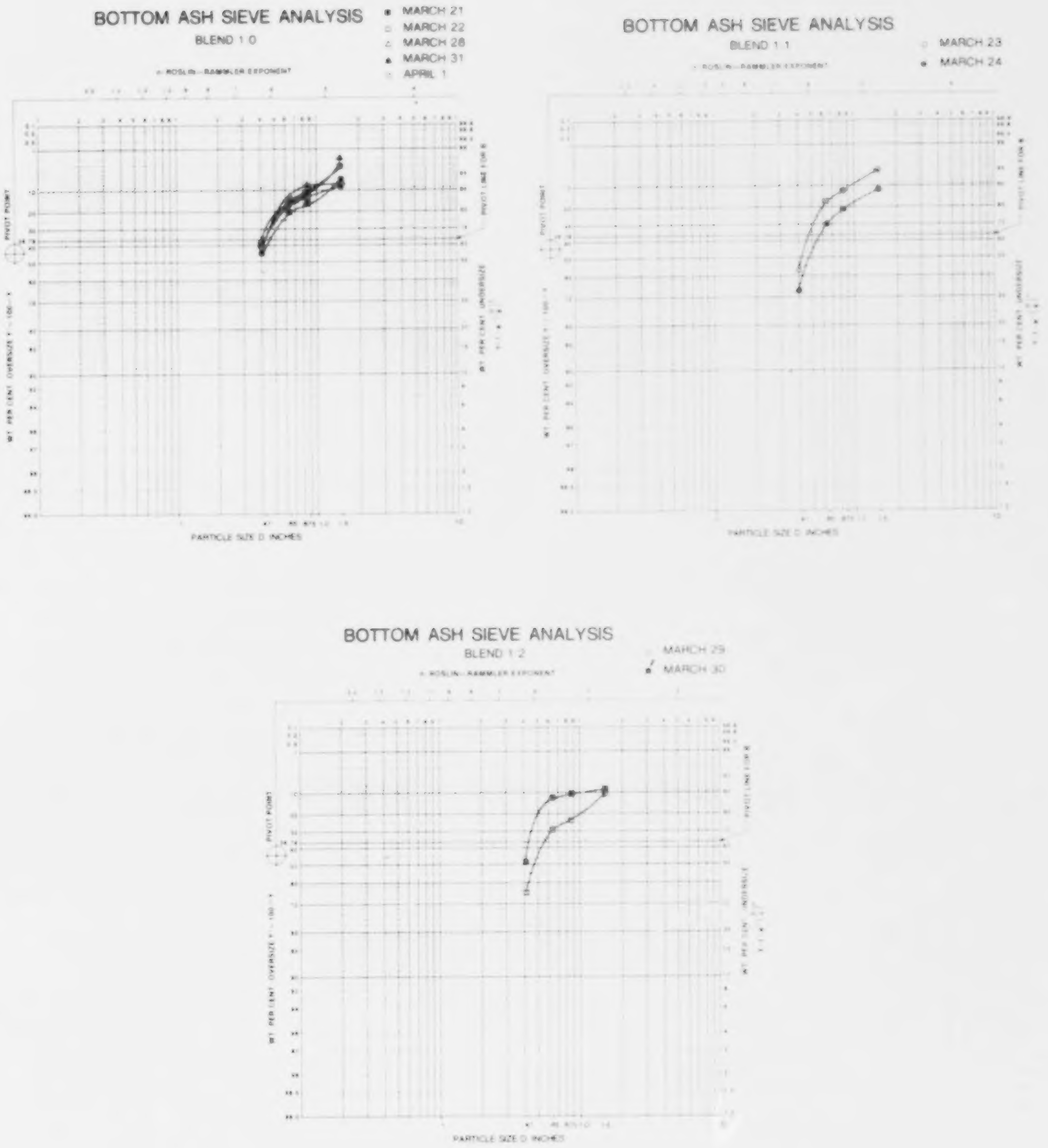

Figure 17. Sieve analysis of bottom ash samples for coal, blend, and dRDF firings.

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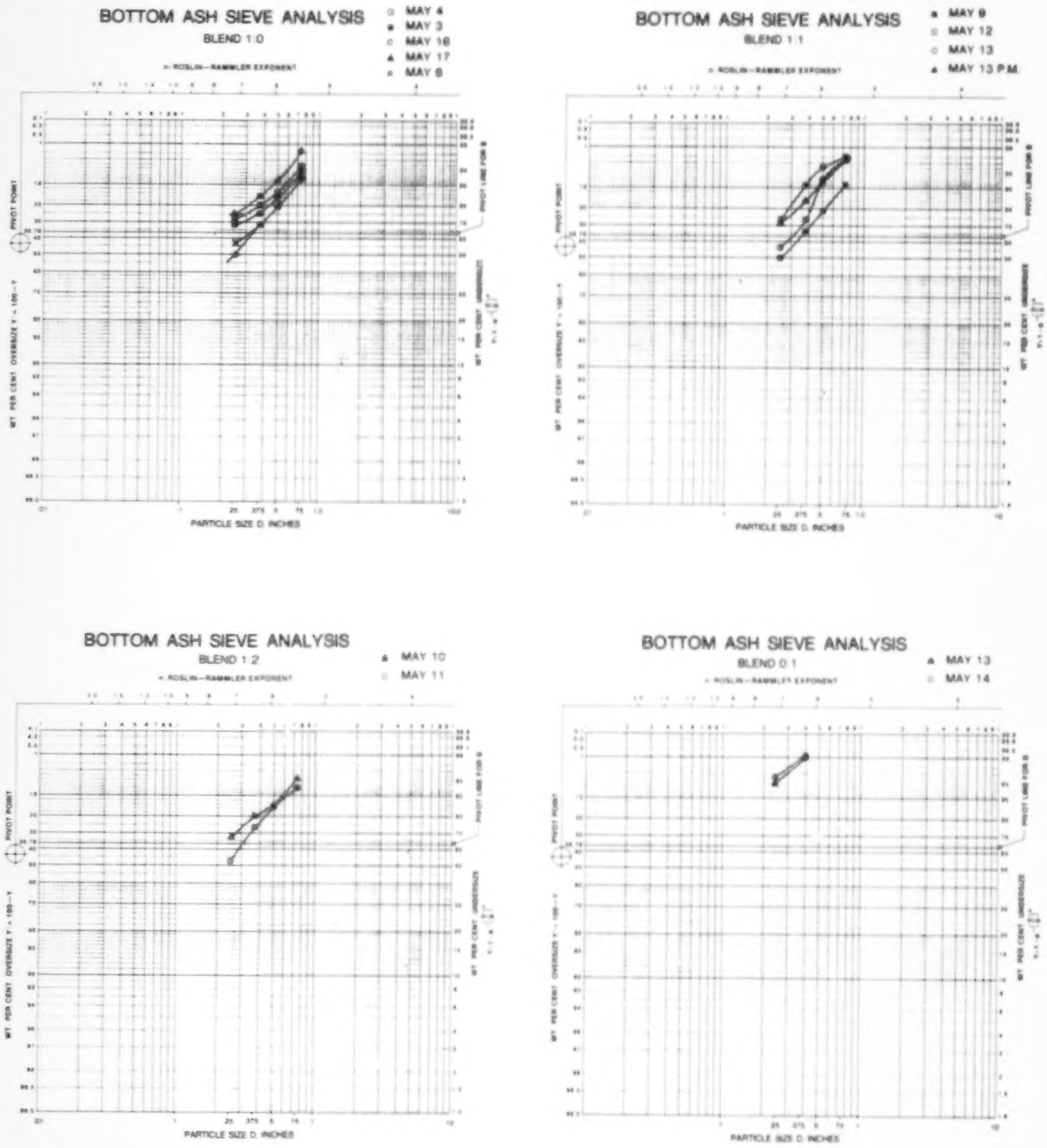

Figure 17 (Concluded)

for 1 hour, it was manually shoveled from the ash pit into tared 55-gallon drums and weighed. As would be expected, the quantity of ash increased with increases in dRDF.

Ash Silo--

The ash silo is used for dry ash storage. The bottom ash and the fly ash are both transferred to the silo by the pneumatic ash handling system. The ash is withdrawn from the bottom of the silo by a rotary drum mixer where the ash is blended with water for dust control before discharge into a truck.

The only problem with this system occurred during 100 percent pellet firing when the bottom ash was so fine that it would not de-entrain properly in the cyclone. Rather, the paper ash particles, which were wetted by the steam in the ejector, carried through the cyclone and eventually plugged the ejector. Although the ejector was easily cleaned, continued maintenance of the ejector will likely require developing some other means for keeping it clear.

Reinjection and Collector Fly-Ash Flows--

To measure the change in rate of fly-ash reinjection into the furnace when changing from coal to dRDF, a secondary measurement technique was used. Because the reinjection and collector dust streams were piped directly into the plant's pneumatic ash handling system, it was impractical to isolate the flow from one collector and weigh it as had been done for the bottom ash. Consequently, the flow was measured by installing a drain tube near the bottom of the collector and reinjector hoppers. Figure 18 illustrates this sampling technique. As fly ash accumulates in the hoppers, it flows down the sides. A portion of that flow will fall into the drain tube. The amount of ash collected in the drain tube over a fixed period of time indicated the relative fly-ash flow in the hopper.

The fraction of ash falling to the ash pit was relatively independent of the type of fuel being used (e.g., it did not matter if the fuel was coal or dRDF), but it was strongly dependent on the ash content of the blend. However, the weight of the carbon fly ash accumulating in the reinjector and collector drain tubes (see Figures 19 and 20) did not appear to have any correlation to the ash content of the fuel. Since the dRDF had a higher ash content than the coal, it was anticipated that the ash flow into the drain tube would increase with increasing dRDF substitution. This occurrence however, was not indicated by the data.

The lack of variation in the ash accumulation in the drain tube as a function of fuel ash content was perhaps due to incomplete burning of carbon or the difference between coal and dRDF carbon fly ash particle gas de-entrainment characteristics. The data shows, however, that combustion improved as dRDF was substituted for coal. Figure 21 shows the carbon content of the reinjector ash as a function of the boiler load and coal:dRDF ratio. While the data has much scatter, a general trend toward improved carbon burnout with dRDF substitution is evident. Consequently, since the decreasing amount of carbon with increasing dRDF substitution tended to offset the increasing ash content of the fuel, the drain tube ash flow measurements for various coal:dRDF blends could be deceptive.

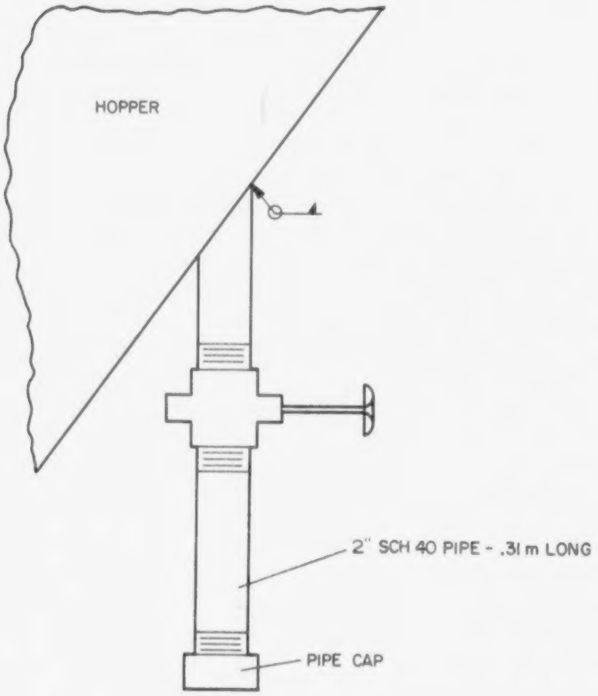
HOPPER
2" SCH 40 PIPE - .31 m LONG
PIPE CAP

Figure 18. Drawing of a typical ash collection drain tube to monitor relative ash flow in collector and reinjector.

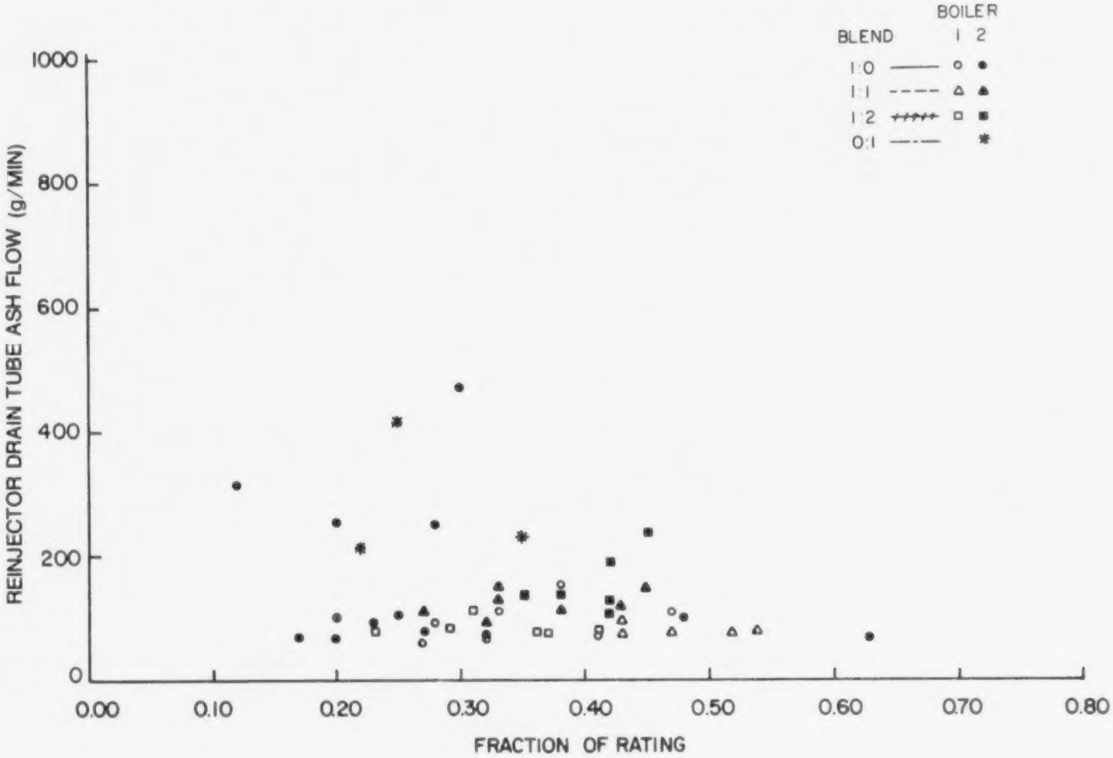

Figure 19. Ash flows into reinjector hopper drain tube for coal, blend, and dRDF firings.

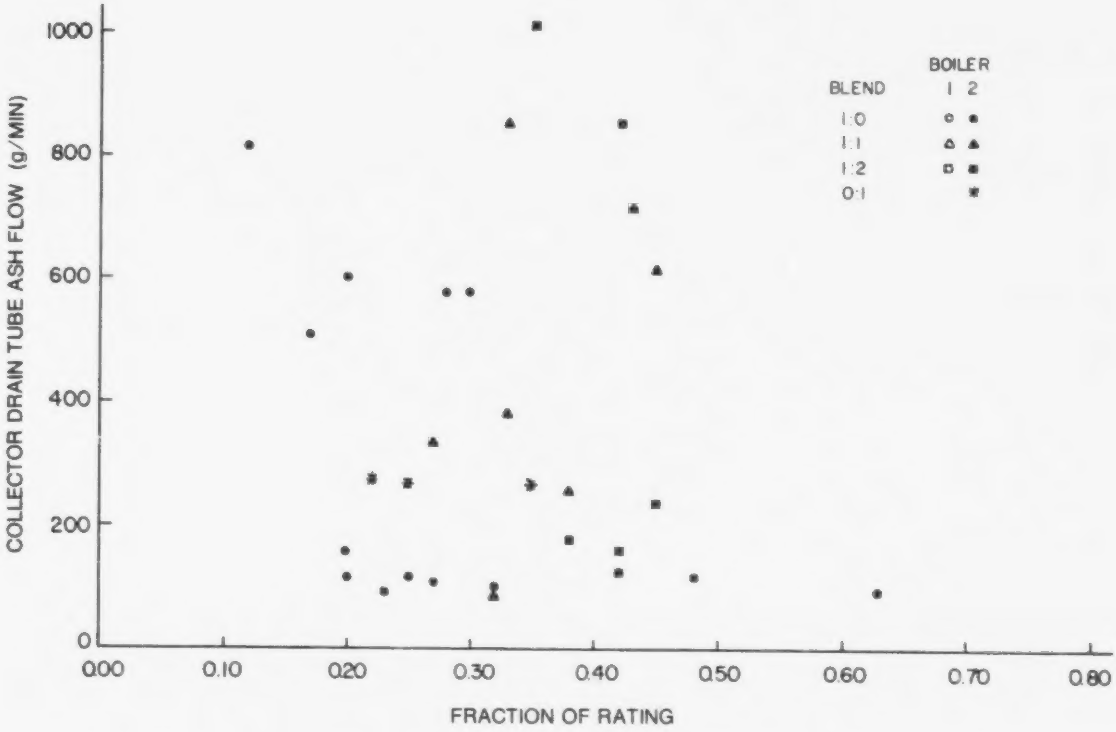

Figure 20. Ash flows into collector hopper drain tube for coal, blend, and dRDF firings.

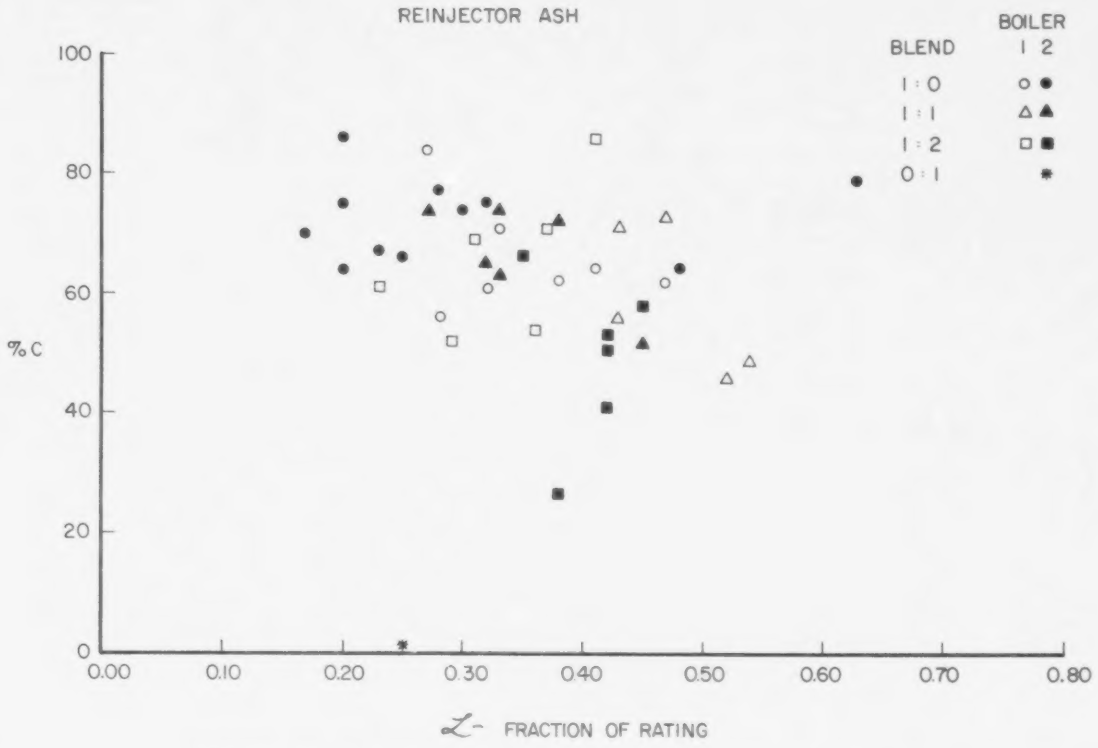

Figure 21. Carbon content of reinjector ash for coal, blend, and dRDF firings.

As dRDF is substituted for coal, the ash distribution becomes finer. Figures 22 and 23 show that the 1:1 and 1:2 size distributions are similar to, but finer than, the 1:0 size distributions. The ash from firing a 0:1 blend produced the highest amount of fines. A possible explanation of this phenomenon is that as more paper is burned, there is an increased amount of fine ash which is easily lofted by the underfire air.

Air and Gas Handling

System Description--

Each boiler has three separate air systems: underfire air, overfire air, and an induced draft fan. The underfire airflow was controlled from the fuel flow to the furnace. The overfire air was adjusted manually to achieve the most smoke-free operations. The induced draft fan was controlled by a draft sensor in the upper part of the furnace to maintain a specified negative pressure in the firebox.

The underfire air and induced draft fans are equipped with both electric motors and steam turbine drives. The overfire air fans are driven by an electric motor.

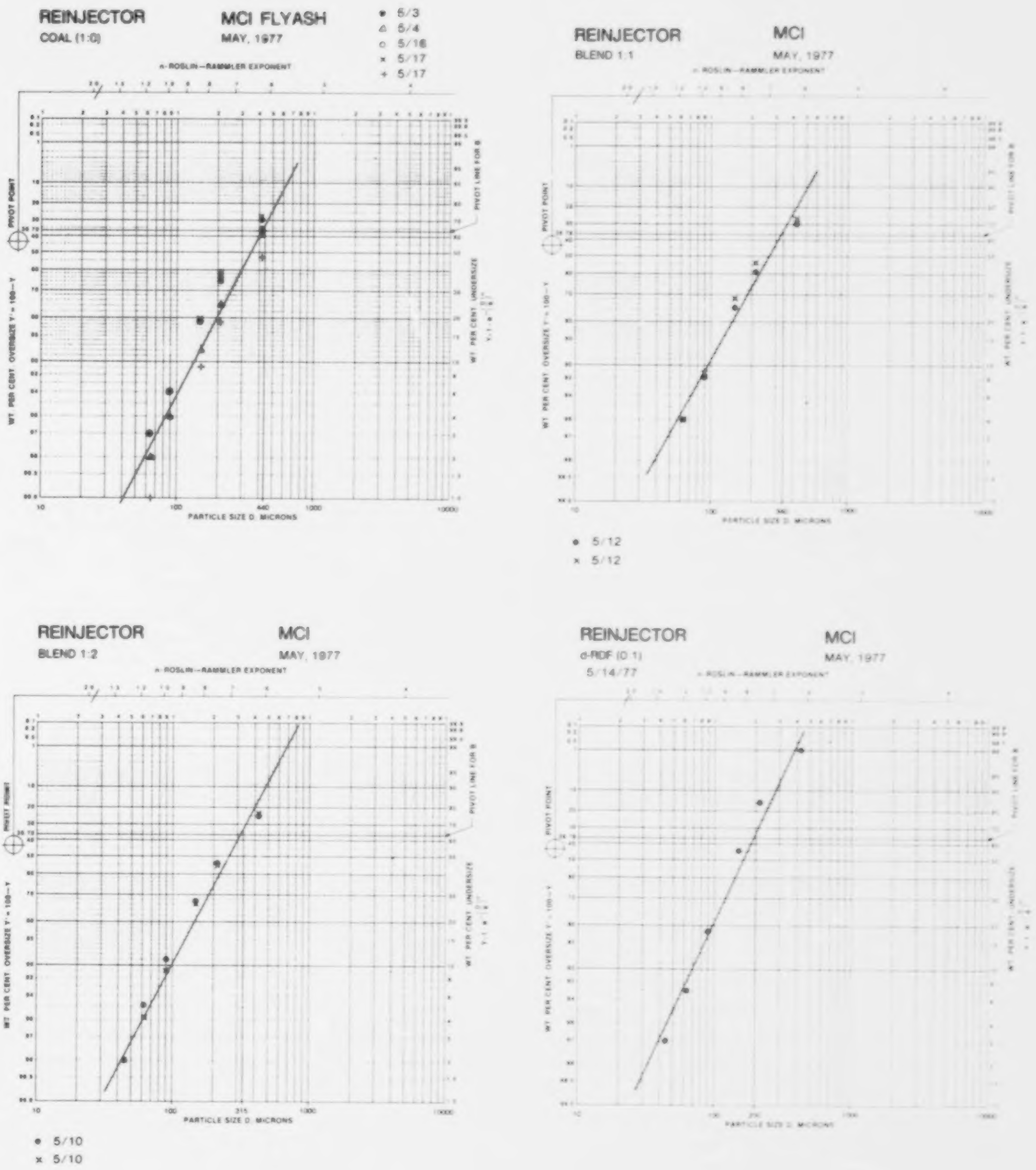

Figure 22. Reinjector ash size distributions for coal, blend, and dRDF firings.

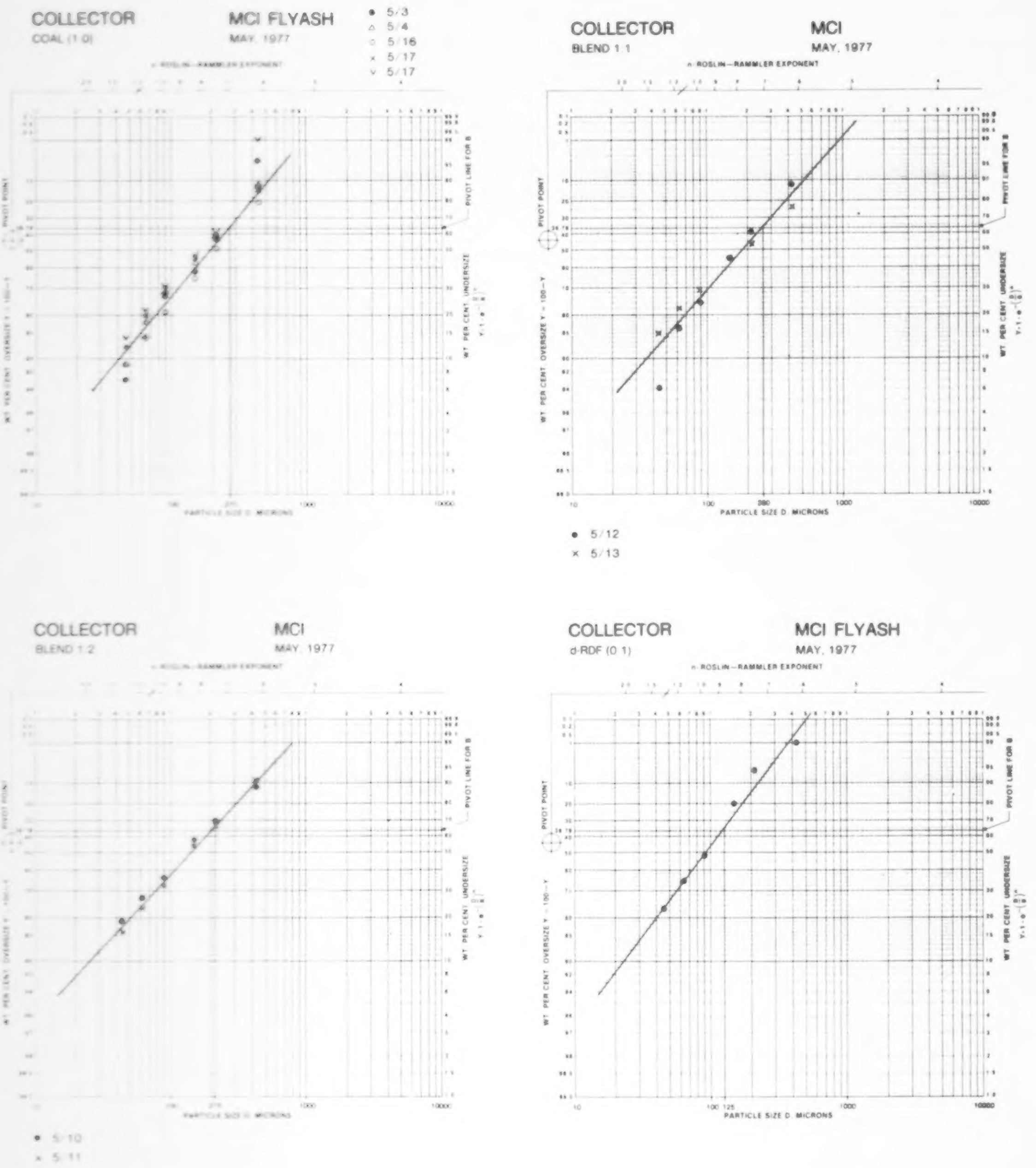

Figure 23. Collector ash size distributions for coal, blend, and dRDF firings.

Underfire Air Setting--

When the underfire air fans were set for manual control to follow the steam flow, a clean ash bed was maintained; but when they were placed on automatic control, clinkering occurred. The controls were designed so that the amount of fuel fed to the furnace is varied to maintain boiler pressure. In addition, the airflow is controlled proportionate to the fuel flow. Consequently, during a load shed, fuel on the grate could deliver an extra 0.6 to 1.3 kg/sec (5,000 to 10,000 lb/hr) of steam due to the lag time associated with this control mode. As a result, the ash bed could change from oxidizing to reducing conditions which promote clinkering. This condition occurred when the airflow followed the fuel feed rate rather than the amount of fuel in the furnace. To prevent this problem during the May testing, the underfire was biased upward as though the boiler were carrying 1.3 kg/sec (10,000 lb/hr) more steam than it actually was. When the controls were set for 50 percent excess air, rapid load sheds induced clinkering. After the air was biased upward to provide 20 percent more excess air, the load sheds caused no problems.

The need for this biasing was attributed to the appreciable amount of underfire air leakage around the grate. When the boiler was inspected before testing, the seals between the grate and the windbox appeared to be tight. However, when a water-cooled lance was used to probe the furnace during operation, the excess air levels at 1 m (3 ft) and 3 m (10 ft) above the center of the grate were 30 and 50 percent, respectively. In the center of the duct leaving the boiler, the excess air levels were about 120 percent. Figure 24 shows the carbon dioxide level inside the furnace compared with that at the furnace outlet. Figure 25 shows the excess air in the breeching. Figure 26 shows the leaning of the flame toward the center of the furnace which confirms the hypothesis of excess underfire air leakage.

In view of the above, it appears that a coal:dRDF blend can be fired at the same settings as coal only if adequate air is available to prevent clinkering during load sheds. In addition, excess air levels of 50 percent should be attainable in a tight boiler since the excess air at the grate in the test boiler with significant air leakage around the grate was 30 percent.

When firing 100 percent dRDF in March, no problems were encountered when the air control was set on manual at an air flow typical of that required when burning a specification stoker coal and supplying a desired steam flow. In May, however, when pellets were first introduced, ignition problems developed when the underfire air was automatically controlled. A malfunction of the air control system resulted in a 600 percent excess air condition on the fuel bed which nearly extinguished the flame. Once the ignition problem was diagnosed and the air controller was put on manual (it could not be biased enough to stay on automatic), the fire returned to normal, and the feeders operated at a low fraction of capacity with steam pressure returning to normal.

Overfire Air Setting--

Combustion air is normally provided through the grate as underfire air so that the fuel is supplied with sufficient oxygen to ensure its complete combustion. However, because of the different combustion rates of various

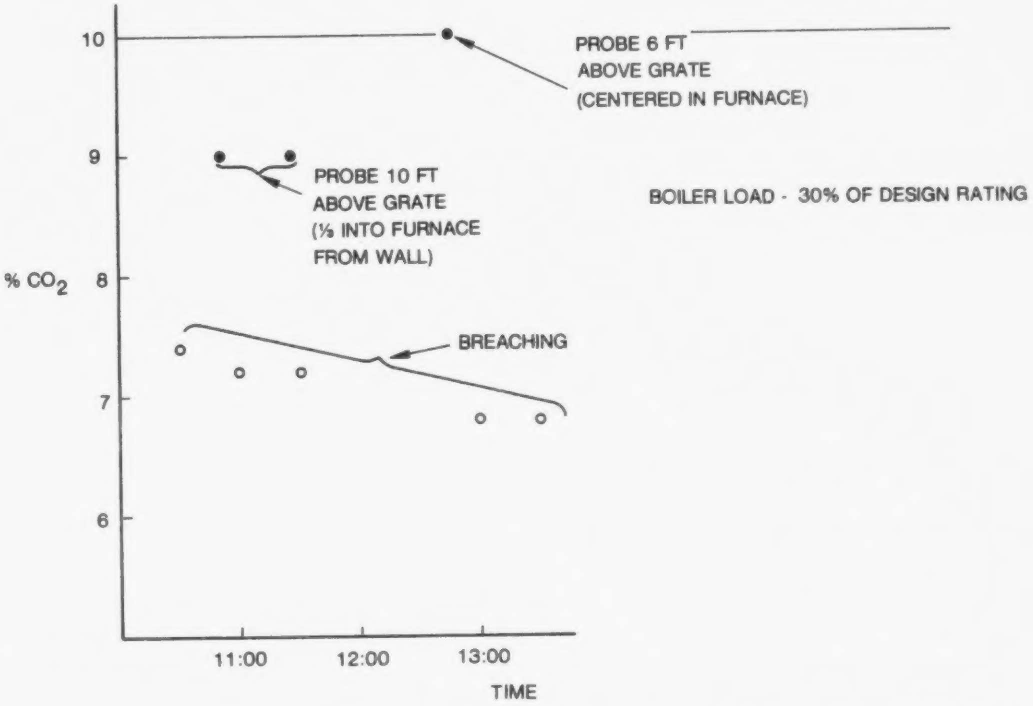

Figure 24. Carbon dioxide levels in furnace vs. time as determined with a water-cooled probe.

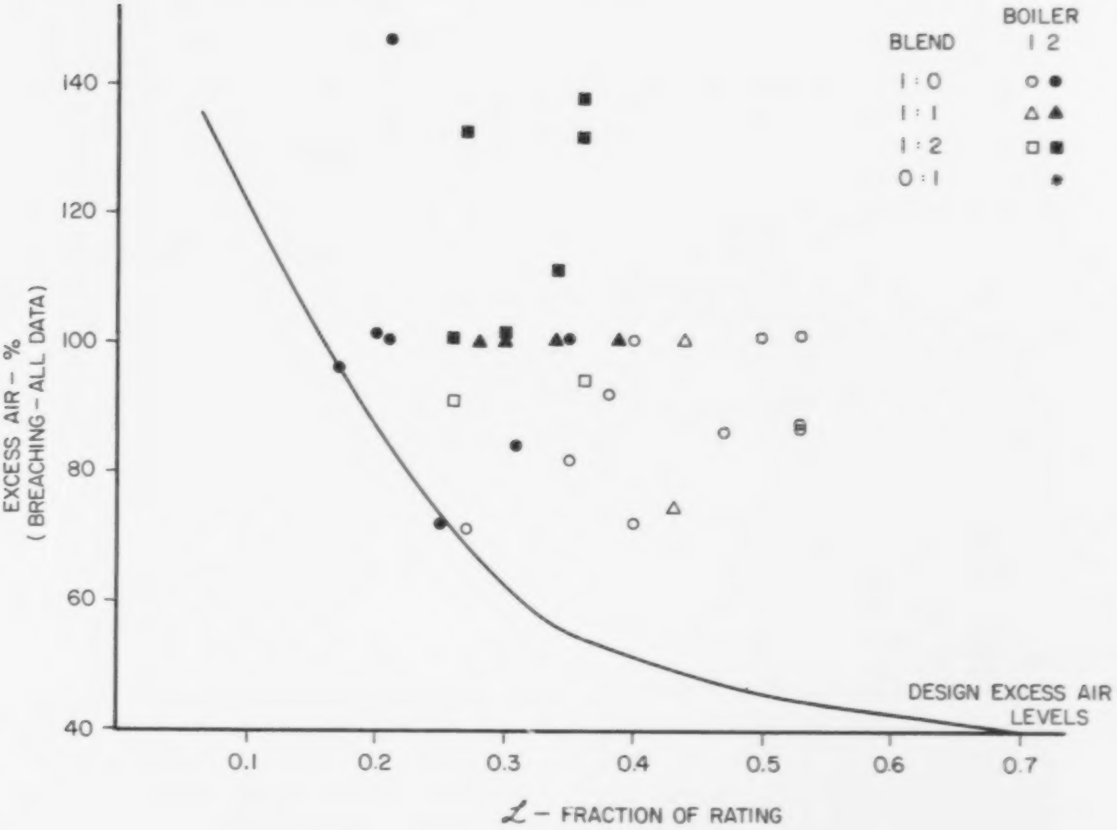

Figure 25. Relationship of furnace excess air level with blend and load.

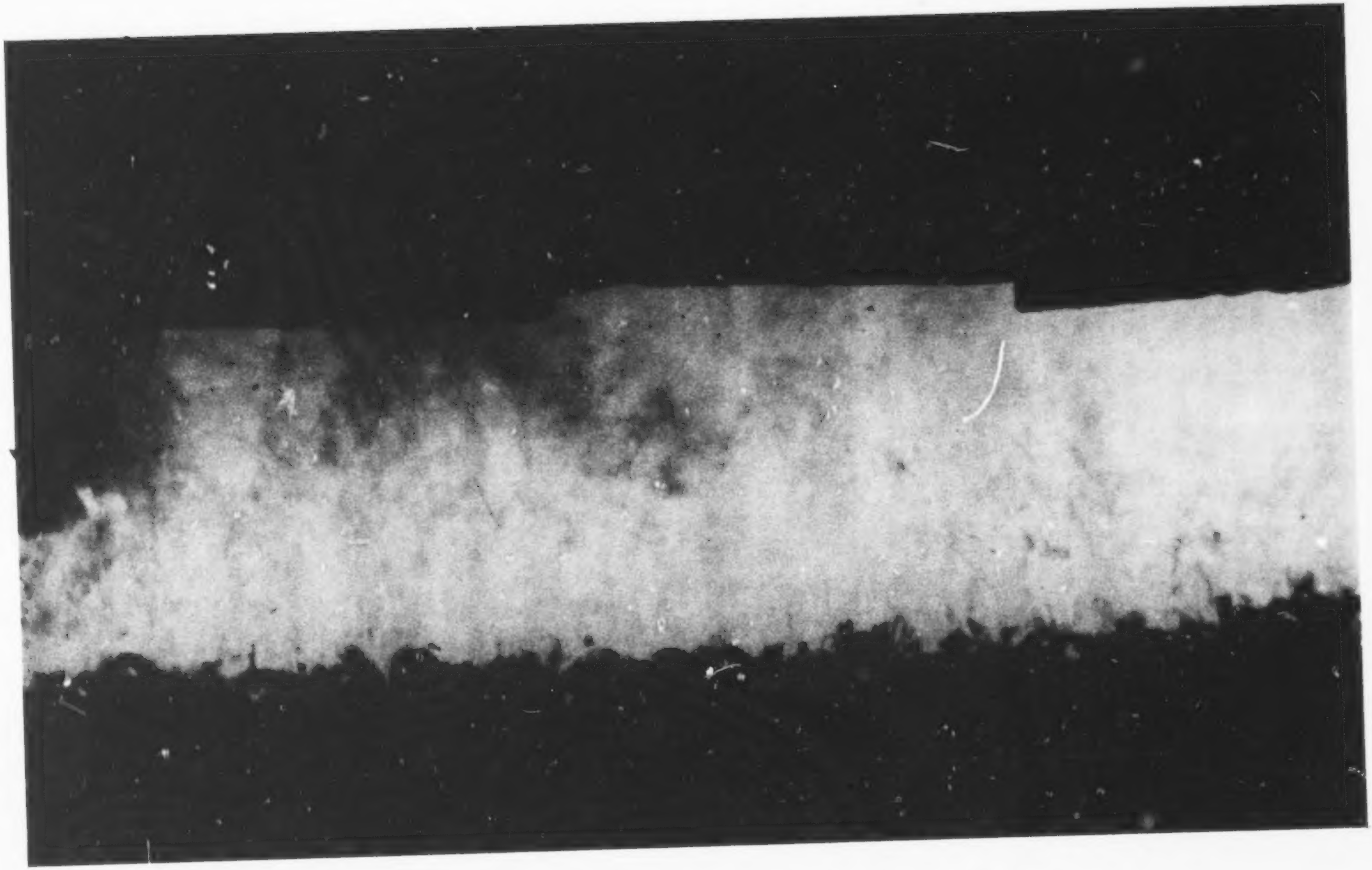

Figure 26. Grate seal leakage forcing flames toward center of furnace during a 1:1 blend firing in Boiler No. 2.

lumps of coal and the nonuniformity of coal distribution onto the grate, some of the air coming up through the grate into the combustion zone is channeled, and it bypasses the areas where it is needed. With such channeling, pockets of pyrolysis gas form above the grate. If these pockets of hydrocarbons pass through the flame zone without being exposed to adequate oxygen to complete combustion, smoking will occur. To prevent smoking, the gases must be mixed so that they do not drift uniformly upward and out of the furnace without combustion. These pyrolysis gases are mixed with overfire air jets. The proper use of overfire air jets is particularly critical when a boiler is being operated at a low fraction of load.

In order to find the proper setting for coal:dRDF operation, the overfire jet pressure was increased in 12.7 mm (0.5 in.) of water increments starting at 12.7 mm (0.5 in.) of water until the opacity meter showed no reduction in smoke with increasing jet pressure. Because of time constraints and the amount of fuel available, this procedure was iterated three times for the front and rear rows of overfire air jets for each blend during the first day of each test. After the minimum smoking settings were determined, they were used in the subsequent tests.

The differences between the settings for coal-only and blend firing were as follows: When firing blend, the air pressure applied to the front 5.08 × 1.9 cm (2 × 3/4 in.) rectangular overfire air jets was reduced from 178 to 114 mm (7 to 4.5 in.) of water while the air pressure applied to the rear 5.08 × 1.9 cm rectangular overfire air jets was increased from 38.1 mm (1 1/2 in.) to approximately 76.2 mm (3 in.) of water. The pressure for the rear jets was increased because the high volatile content of the dRDF produced a large fireball which enveloped more of the furnace volume than the fireball from coal-only firing. The pressure for the front jets was decreased because the fuel was burning more in suspension and further to the back of the furnace. Consequently, there was only burnt-out fuel in the forward portions of the grate which required less overfire air than normally needed for coal.

Regardless of the blend employed, including 100 percent pellets, the amount of overfire air required was the same.

Induced Draft Fan--

The induced draft fans were adequate for all the tests performed. However, the boilers were not fired above 70 percent of rating on blends because of limitations in steam demand and make-up water equipment. Attempts to operate at 100 percent of boiler design capacity by blowing steam were aborted when it was determined that the make-up water equipment had insufficient capacity to handle the make-up water flow. Consequently, it could not be determined whether the existing induced draft fans have sufficient capacity for firing various blends up to 100 percent of rating.

A study of the fuel properties listed in Table 6 reveals that the air:fuel ratio for coal-only and coal:dRDF blends is approximately the same with blends requiring slightly less air per megajoule heat release than coal. This is particularly significant because if coal and blends can be fired at the same excess air levels, the amount of gas passing through the boiler to the collectors and fans will be the same when the boiler efficiencies are equivalent. However, as discussed subsequently, the efficiency of a boiler firing dRDF is expected to be slightly lower than the efficiency of a boiler firing coal because of the higher hydrogen content and bound moisture of the blend.

If the feeders do not limit the substitution ratio which can be used without derating the boiler, then the fan capacity could become the limiting factor. The induced draft fan, rather than either the overfire air blower or the underfire air fan, would most likely have an insufficient capacity.

Furnace Performance

After the fuel has been mixed with air and ignited, it burns to release the chemical energy in the fuel. The heat is recovered in two different sections of the boiler to produce steam. First, some heat is transferred by radiation to boiler tubes in the furnace walls. Second, additional heat is withdrawn from the gases as they pass through the convection section of the boiler. The overall performance of a furnace-boiler combination depends to a large extent on the radiant heat transferred in the furnace and the removal of sufficient heat from the combustion products so that the fly ash is solid and not molten in the convection section. The heat transfer characteristics of the rest of the boiler are governed by the gas properties and the mass flow rate.

Heat Release Rate--

The design heat release rates for Boilers No. 1 and No. 2 were: 961 $MJ/m^3/hr$ (25,800 $Btu/ft^3/hr$) and 616,000 $MJ/m^2/hr$ (543,000 $Btu/ft^2/hr$) for Boiler No. 1 and 1002 $MJ/m^2/hr$ (26,900 $Btu/ft^3/hr$) and 662,000 $MJ/m^2/hr$ (583,000 $Btu/ft^2/hr$) for Boiler No. 2. Figures 27 and 28 show the heat release rates attained during the tests. The maximum heat release rates were low because of low steam demand requirements. Even in the coldest time of the winter, only 7.1 kg/sec (56,000 lb/hr) of steam were required to meet the heating needs of the Maryland Correctional Institute. Consequently, the tests do not show the effect of coal:dRDF blends on boiler performance at or near design heat release rates.

Flue Gas Temperature--

Of particular concern to a boiler operator is the temperature of the gas leaving the boiler. This temperature indicates the amount of potentially available energy that is lost to the environment. Figure 29 is a graph of the flue gas temperatures in the furnace when firing coal-only and coal:dRDF blends. The exhaust gas temperature characteristics of Boilers No. 1 and No. 2 differ. The exhaust temperatures also differ when firing coal-only or when firing coal:dRDF blends for the same boiler load.

Fouling, Slagging, and Wastage--

Coal:dRDF blend firing resulted in occasional slagging, slight fouling, and perhaps slightly higher than normal wastage. Since these are areas of major concern to potential fuel users, a detailed discussion is presented although the total evaluation effort is not complete or conclusive because of the relatively short duration of testing and the low boiler loads maintained throughout the tests.

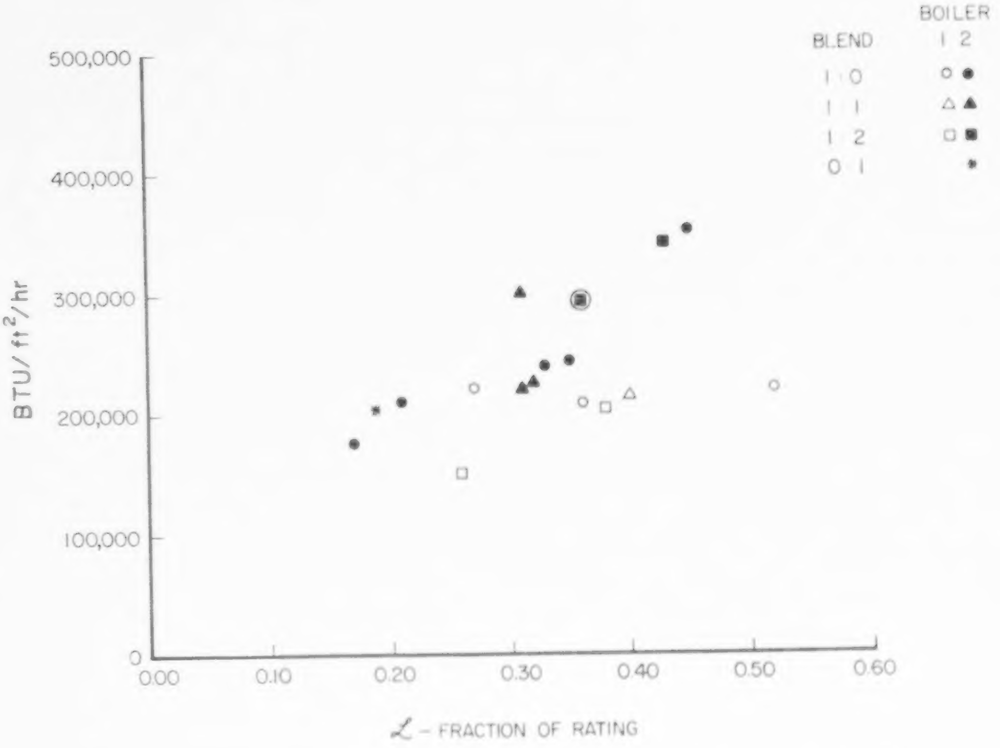

Figure 27. Heat release rates per unit grate area for coal, blend, and dRDF firings.

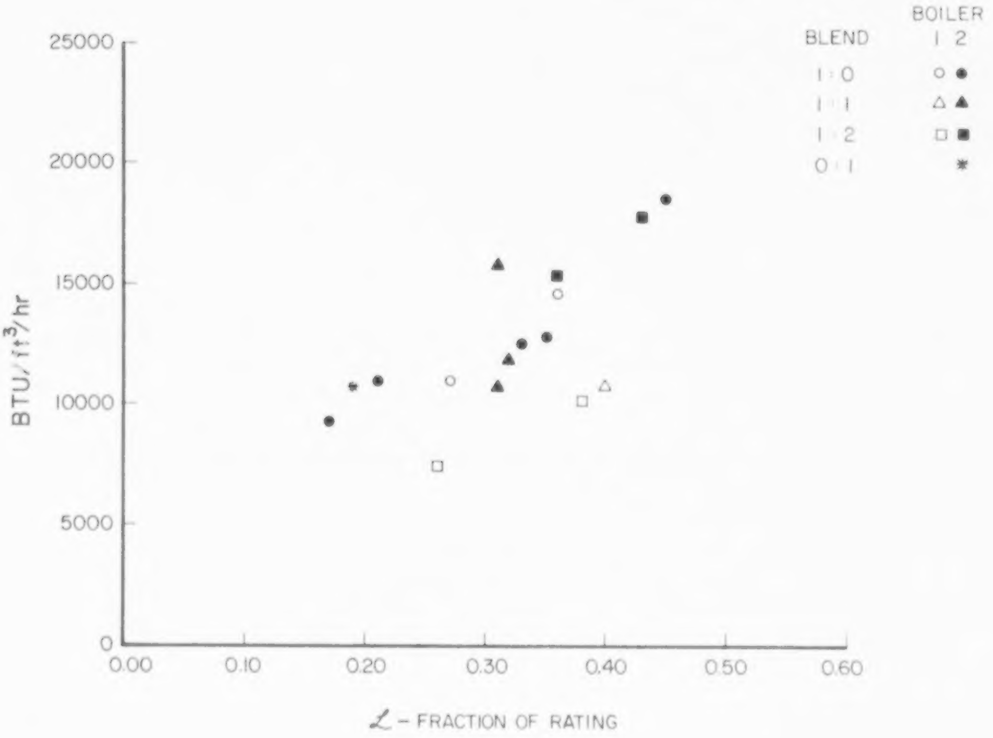

Figure 28. Heat release rates for coal, blend, and dRDF firings.

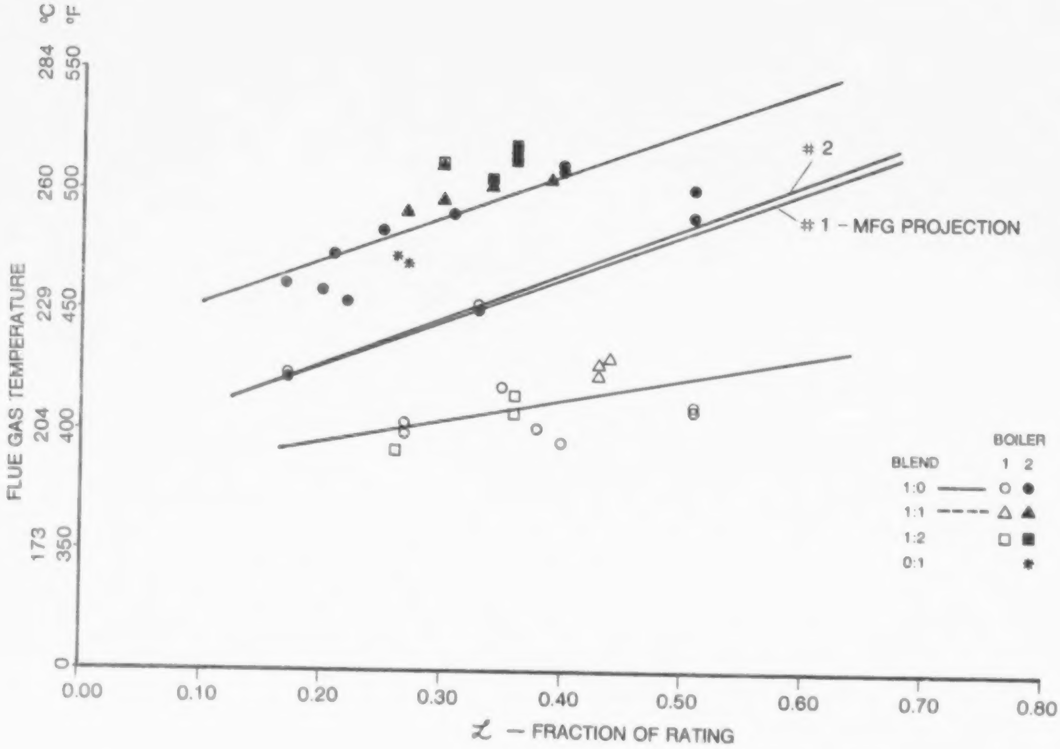

Figure 29. Effects of blend and load on flue gas temperature.

Since the boilers were operated at low loads throughout the tests, furnace temperatures were not high. Even under these conditions, the boiler deficiencies were corrected with simple adjustments. The findings imply that a boiler owner should not anticipate immediate failures. The long-term effects, however, are as yet unknown.

When pellets impinge on a wall, they tend to stick and burn because of the low fusion characteristics of the dRDF. For fuels with a higher ash fusion temperature, the material rebounds and falls to the grate where it is burned. Severe slagging occurred during a portion of the May tests when one-third of the rear wall of the furnace opposite Spreader No. 1, which was maladjusted, was covered with slag. The remaining two-thirds of this wall remained clear. This slag was generally loose and could be easily removed. Fouling also accumulated rapidly on the leading rows of the convection section of the boiler in line with the maladjusted spreader. The remaining two-thirds of the convection section remained clean. The fouling was very loose, was easily removed by rapping, and had a porous structure. At the end of the blend firing, the leading tube elememts had a velvet-like ash accumulation. The same type of coating was found at the conclusion of the low-grade coal burning in December. The potential hazard of this coating cannot be assessed.

After the spreader throw on Spreader No. 1 was adjusted, the accumulation ceased. By the time the boiler was brought off line 8 days later for inspection, the slag had sloughed off. Inspection of the furnace interior revealed that a glassy slag layer had accumulated on the lower portion of the side wall where a grate clinker had contacted the wall. This material was easily removed.

The reducing atmosphere hemispheric fusion temperatures for the ash processed through the system for the December, March, and May tests are graphed in Figures 30 through 32. The low December ash fusion temperatures for coal explain the clinkering observed. The March and May results show that blending coal and dRDF depresses the fusion temperature of the coal. Interestingly, the dRDF-only bottom ash shows a higher fusion temperature than coal. If the glass fragments blow out of the furnace while the fuel is in suspension and leave only paper ash, a higher fusion temperature is possible.

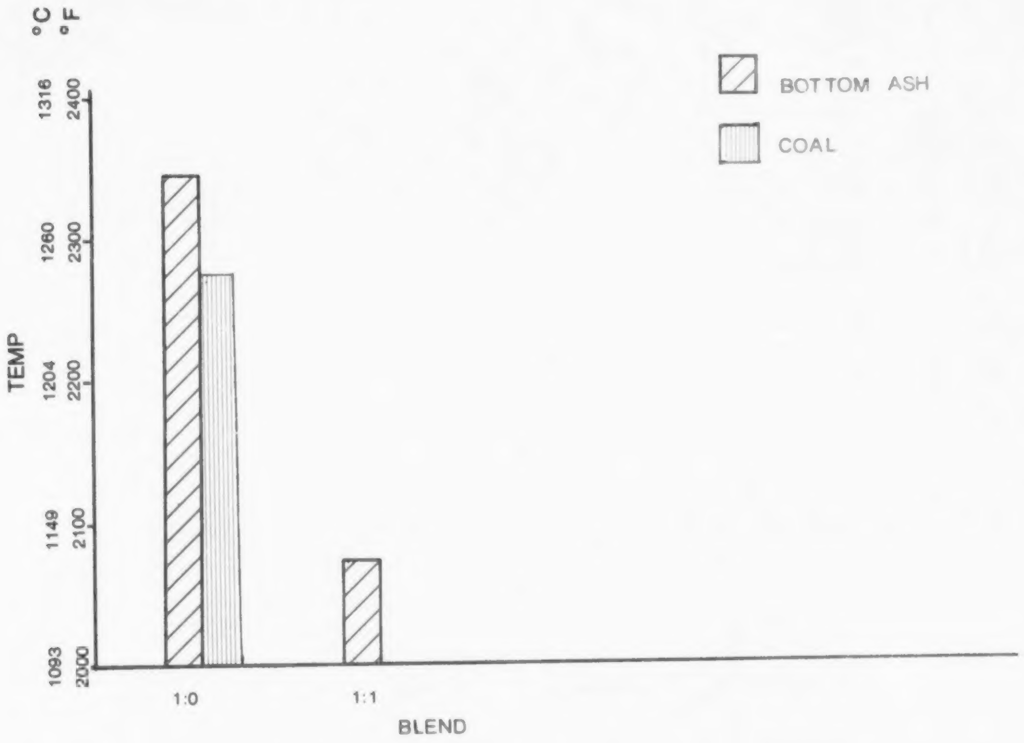

Figure 30. Variations in ash fusion hemispheric temperatures under reducing atmospheric conditions during December runs.

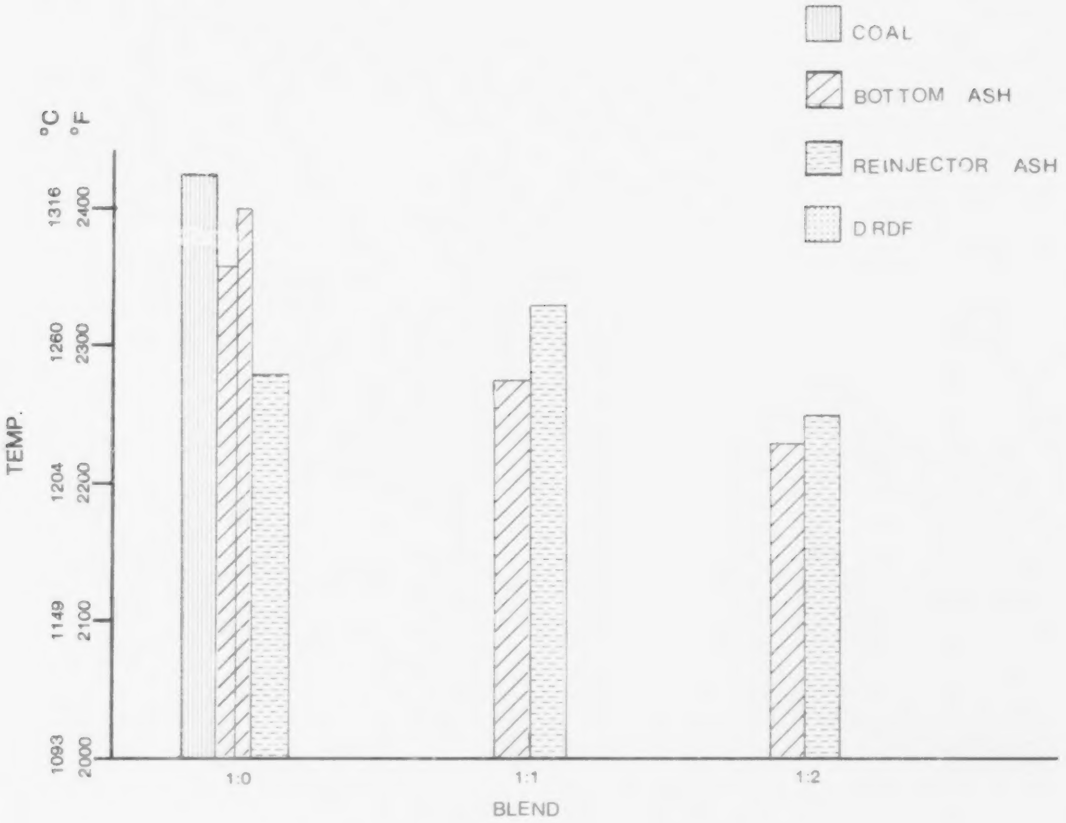

Figure 31. Variations in ash fusion hemispheric temperatures under reducing atmospheric conditions during March runs.

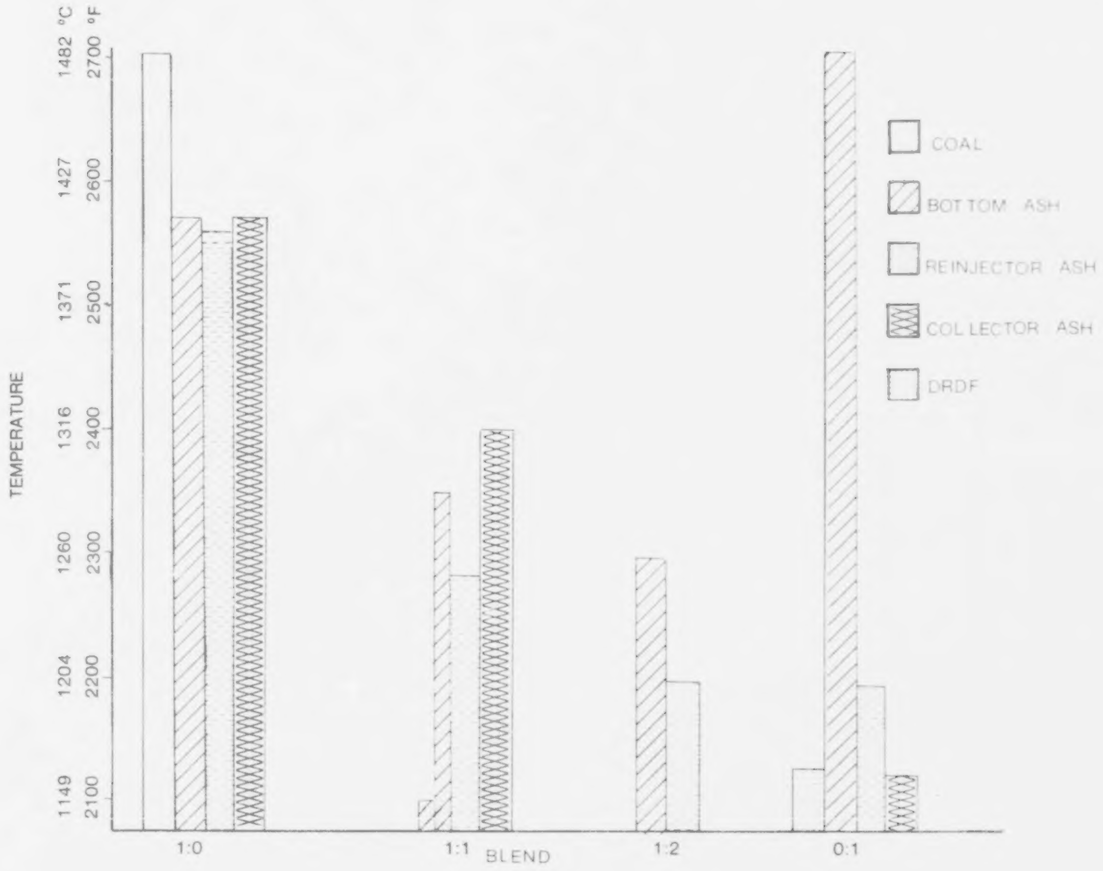

Figure 32. Variations in ash fusion hemispheric temperatures under reducing atmospheric conditions during May runs.

In Figures 33 and 34 the flue gas temperature plots before and after the boiler was fired with blends show that there was some change in the characteristics of the heat transfer surface. Because the "after" data lie outside the confidence band for the "before" data, the heat transfer surface had deteriorated somewhat. The blend ash was more insulating and/or more fouling than the coal-only ash. The increase in exhaust gas temperature was greater after 48 hours of blend firing in March than after 136 hours of blend firing in May. It should be noted however that because different coals were used for the two tests, the fouling may be related to the mixture properties and not just to the presence of dRDF.

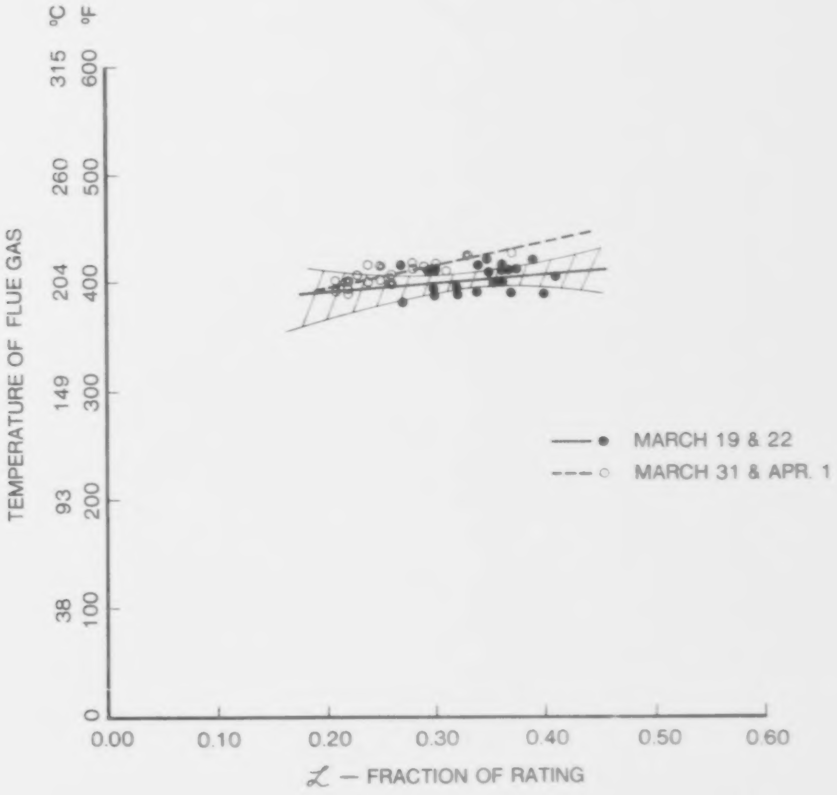

Figure 33. Effects of blend and load on flue gas temperature before and after a test.

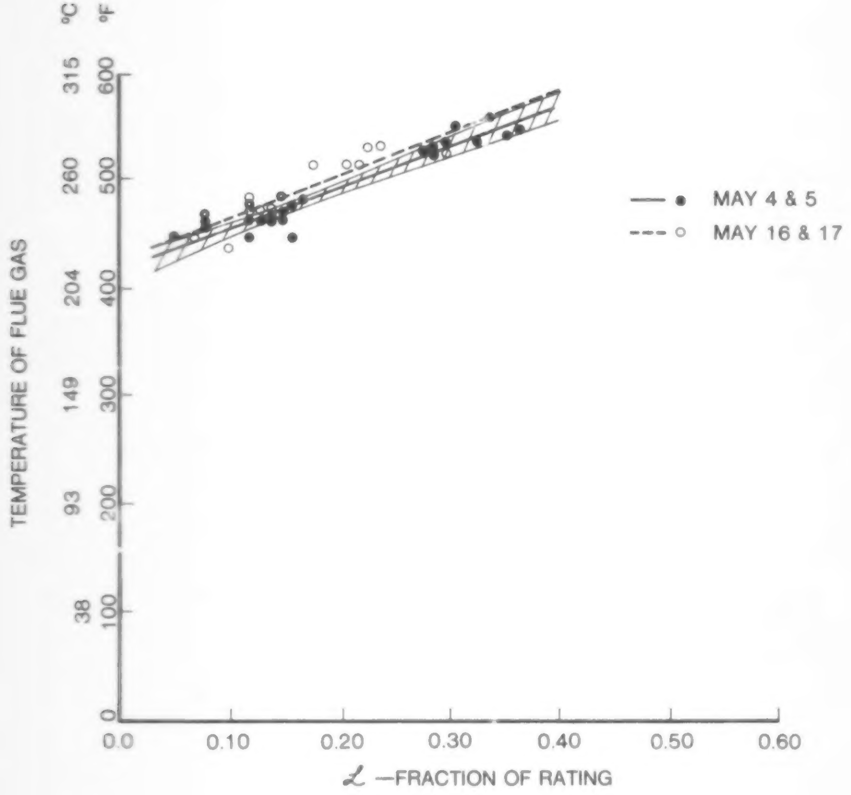

Figure 34. Effects of dRDF and load on flue gas temperature before and after a test.

During the May tests, eight corrosion test specimens were installed on the downcomers in the rear screen wall 1.52 m (5 ft) above the fuel bed. These specimens were clamp-on erosion shields similar to the one shown in Figure 35. Since the shields were bolted in place before bringing the boiler on line, they were exposed first to coal-only firing (1:0); then to 1:1, 1:2, and 1:1 blend firings; next to 0:1 (100 percent pellets) firing; and finally to coal-only firing again. At the end of 478 hours of exposure, the specimens were removed from the furnace and cleaned by the procedures described in Corrosion Engineering.[2] The weight loss of the specimens was converted to a wastage rate in mils per year by Equation 4.4.

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[2] Fontana, M. G., and M. D. Green. Corrosion Engineering. McGraw-Hill, N.Y.C., 1967.

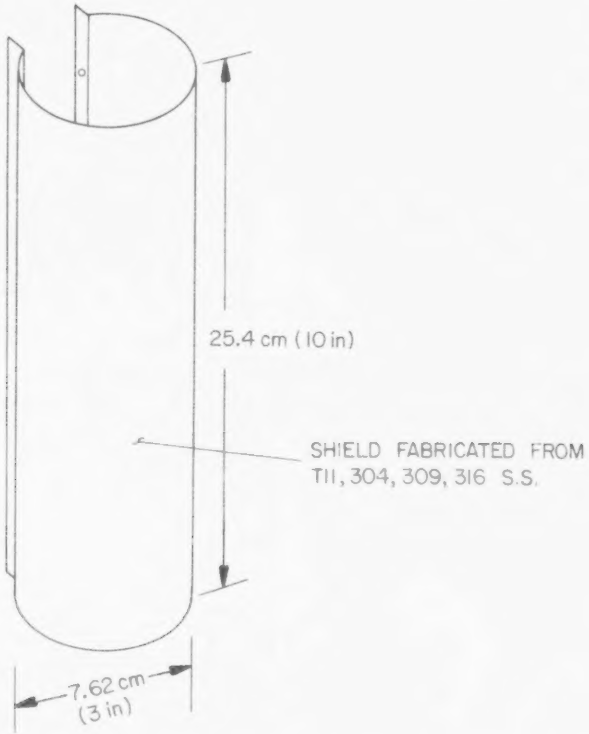


Figure 35. Drawing of typical clamp-on corrosion test shield.

$$\text{MPY} = \frac{534\ W}{DAT} \qquad (4.4)$$

where W = weight loss, mg
D = density of specimen, g/cm^3
A = area of specimen, in.^{2}
T = exposure time, hr

The wastage rate was less than 127 micrometers (5 mils) per year for carbon steel while the wastage (weight loss) of some stainless steel specimens (309 and 310) was not even detectable.

One specimen of 1018 cold rolled steel was in line with the maladjusted spreader. It had a relatively high wastage. Since the surface of this material was exposed to burning material, it was in a strong reducing atmosphere. A twin test specimen not subjected to fuel impingement had a wastage rate of only 76 micrometers (3 mils) per year. Table 8 lists the data used to calculate the wastage rates. While the data provided by this corrosion test provides some guidance, further corrosion testing needs to be carried

TABLE 8. METAL WASTAGE RATE DATA FOR EIGHT SPECIMENS

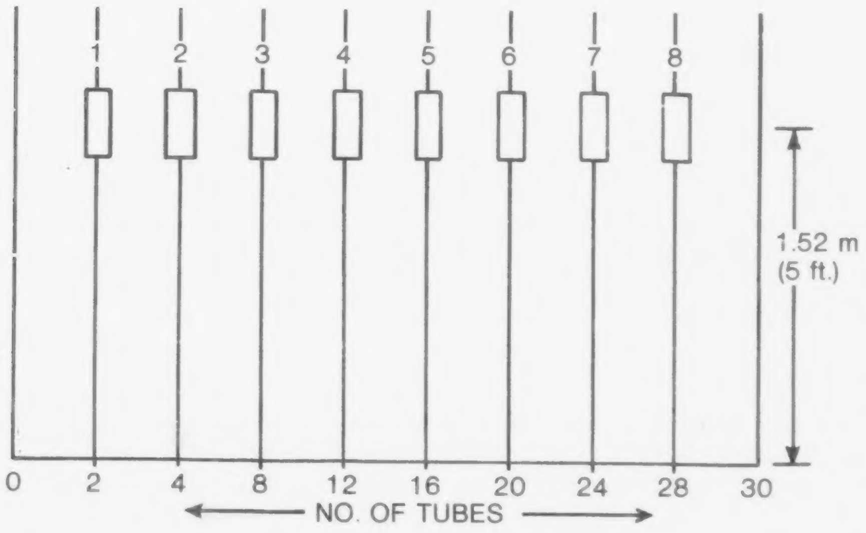
					Specimen			
No.	Material	Location	$\frac{W}{mg}$	$\frac{D}{g/cm^3}$	$\left(\frac{A}{in^2}\right)$	$\frac{T}{hr}$	Mils/v	mm/y
1	1018	1	19310	7.86	100.00	478	2700*	.69
2	304	2	3620	8.02	98.75	478	5.00	.13
3	1018	3	2007	7.86	98.75	478	3.00	.08
4	304	4	4111	8.02	97.50	478	6.00	.15
5	309	5	n/d	8.02	99.38	478	n/d	--
6	310	6	50	8.02	100.00	478	0.07	.002
7	309	7	240	8.02	98.75	478	0.34	.009
8	310	8	n/d	8.02	98.75	478	n/d	--

On Line 1400 April 27, 1977

Elapsed Time
478 Hours

Off Line 1200 May 17, 1977

*Specimen in line with spreader spraying fuel directly on the back furnace wall.



out over longer periods of time (6 months to 1 year) with the boiler operating at or near rated capacity.

Firing Phenomenon--

During the combustion of a series of different mixtures, the coal:dRDF blends seemed to perform as well in the furnace as coal. The principal differences at equivalent loads were that as the dRDF substitution increased, the height, intensity, volume, and violence of the fireball increased correspondingly. Moreover, because of the intermingling of paper platelets with the fuel, more sparklers or live pieces of glowing char were carried by the combustion products toward the heat transfer elements. These sparklers increased as additional dRDF was introduced into the furnace.

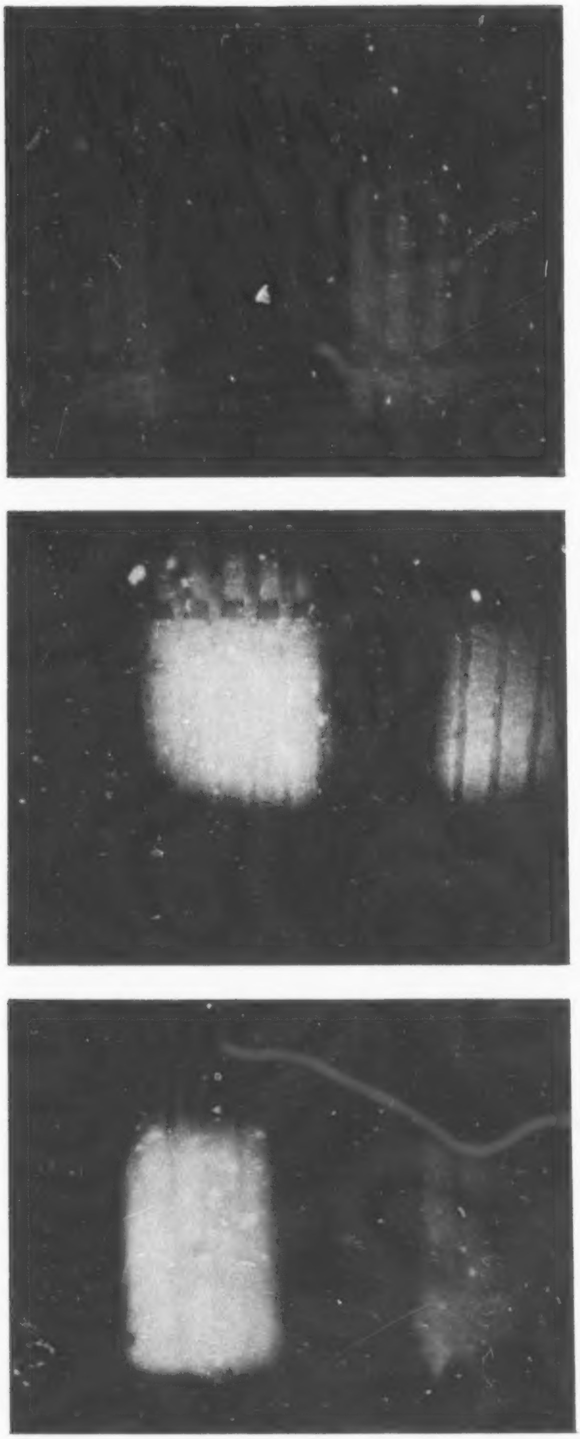
Figure 36, a set of photographs taken through a port in the side wall of the furnace 3.3 m (10 ft) above the grate, shows the extent to which the flame filled the furnace volume. As seen in the progressive photographs, as the dRDF subsitution ratio increased, the number of sparklers and the height, intensity, violence, and volume of the fireball increased.

Figure 37, a photograph taken through the tube removal hatch in the top of the furnace, shows the fire distribution for a 1:1 blend. As seen in this figure, the furnace front has a relatively good burnout, and the furnace rear has a square fire line. The two zones of high-intensity flame in the fire bed indicate that the fuel was spread in two distinct waves: one at the rear of the furnace and the other in the middle of the furnace. This nonuniform spreading was not detected during the cold flow test. However, it did not seem to have any impact on the degree of burnout. The lighter fire to the front left was the result of starving Spreader No. 2 to rectify a worn rotor deficiency which caused an excessive left throw of the fuel.

The radiant heat transfer characteristics of the fireball probably improved as more dRDF was substituted for coal. Figure 38 shows flame temperature versus load as a function of blend. The flame temperature was measured by a Leeds & Northrup optical pyrometer focused on the middle of the fireball at the center of the furnace. Since an optical pyrometer measures the product of emissivity and temperature, an increased reading would indicate that the furnace radiant heat transfer characteristics have improved (assuming excess air remains constant). Consequently, the data indicates that substituting dRDF for coal would likely have a slightly beneficial effect on the heat absorbing capacity of the furnace.

Boiler Controls

The boiler controls in the Hagerstown plant are typical of those installed in heating plants in the mid 1960's. They consist of a master controller which modulates the fuel supply in response to changes in boiler pressure. As the steam demand on the facility increases, the pressure in the steam distribution system decreases, and the amount of fuel introduced into the furnace is increased. The underfire air is modulated in response to fuel flow. In response to load changes, the cam connecting the underfire air to the fuel flow causes the air to modulate to "optimum" firing conditions. Consequently, when there is a load shed, the airflow drops while there is



1:1 Blend Firing

1:2 Blend Firing

0:1 dRDF Firing

Figure 36. Furnace flames viewed at 3.3 m (10 ft) above the grate during blend and dRDF firings.

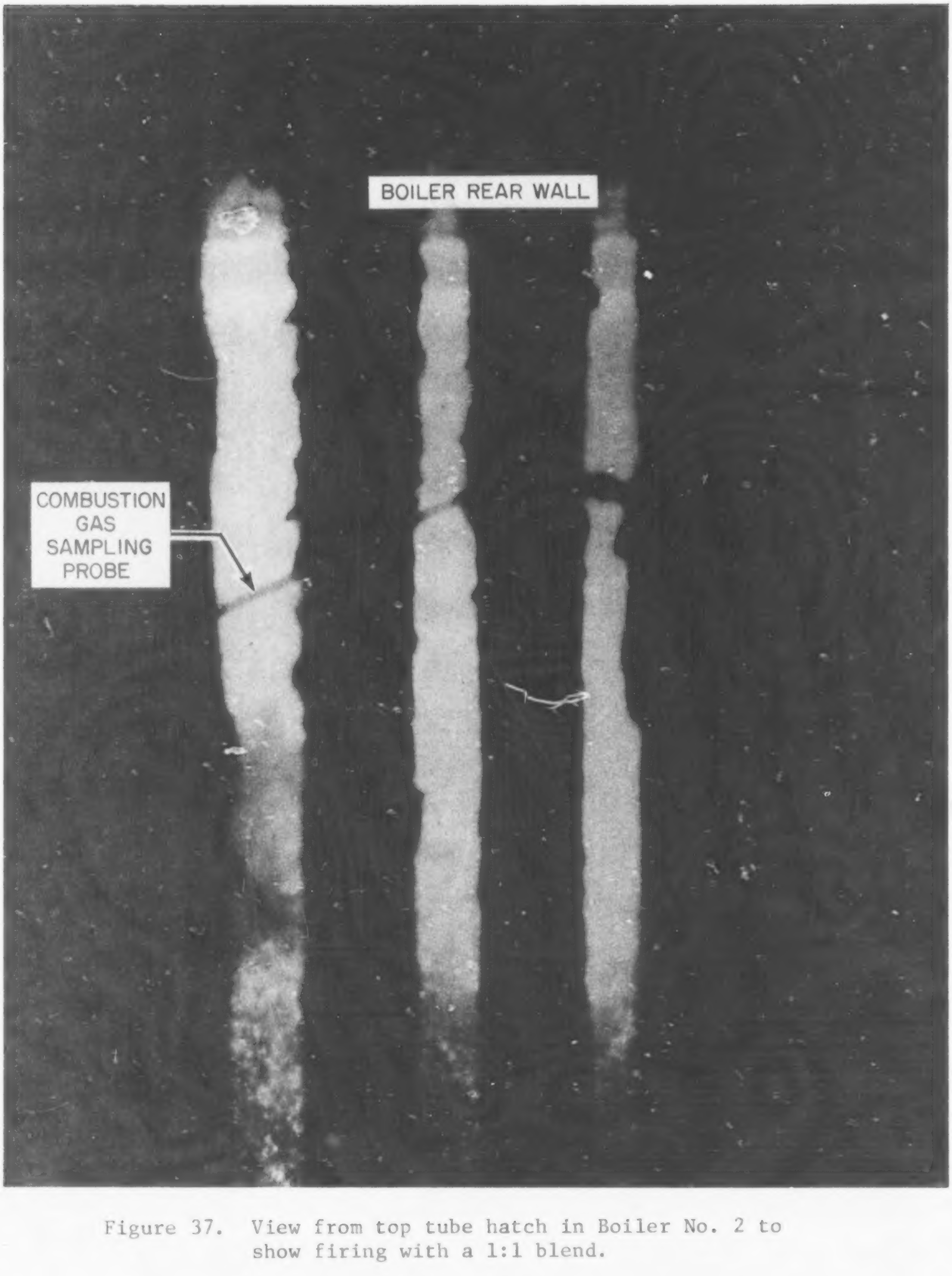

BOILER REAR WALL
COMBUSTION GAS SAMPLING PROBE

Figure 37. View from top tube hatch in Boiler No. 2 to show firing with a 1:1 blend.

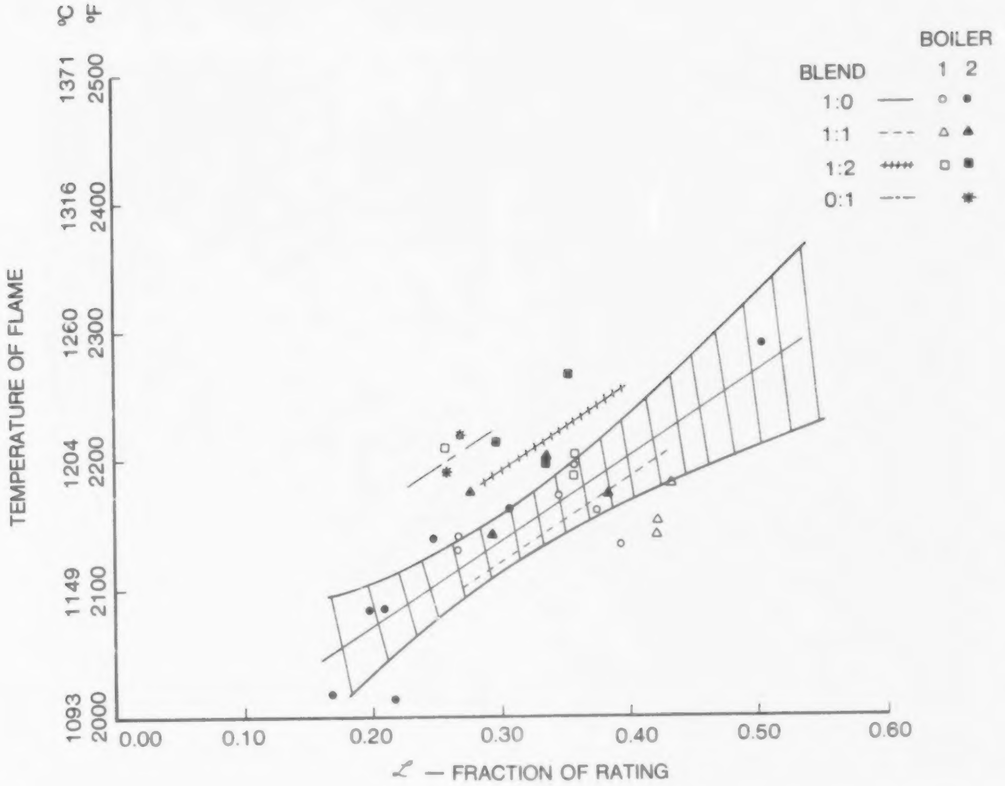


Figure 38. Effects of blend and load on flame temperature measured with an optical pyrometer.

still fuel in the furnace for the higher load level. During such a load change the fuel bed has reducing conditions. Conversely, during a load gain the air input leads the fuel increase, and the fuel bed has oxidizing conditions. This type of control network can cause problems when the fuel on the grate is a low fusion coal or a coal:dRDF blend. During the co-firing tests, some clinkering occurred during load sheds. This clinkering was overcome in the tests by biasing the underfire air control upward. With a combustion control system designed to maintain constant oxygen levels in the flue gas, this clinkering should not occur.

The control system and feeders allowed the boiler to follow the load without any discernable difference in pressure fluctuations in the header when firing coal only and a 1:1 blend. Circular charts for the steam pressure are shown in Figure 39. The modulations in steam pressure were minor for coal only and a 1:1 blend; however, when a 1:2 blend was fired, the feeders were volume-limited and, as a result, had a lag such that the pressure modulated 7 to 14 kPa (1 to 2 psi) in a sawtoothed pattern.

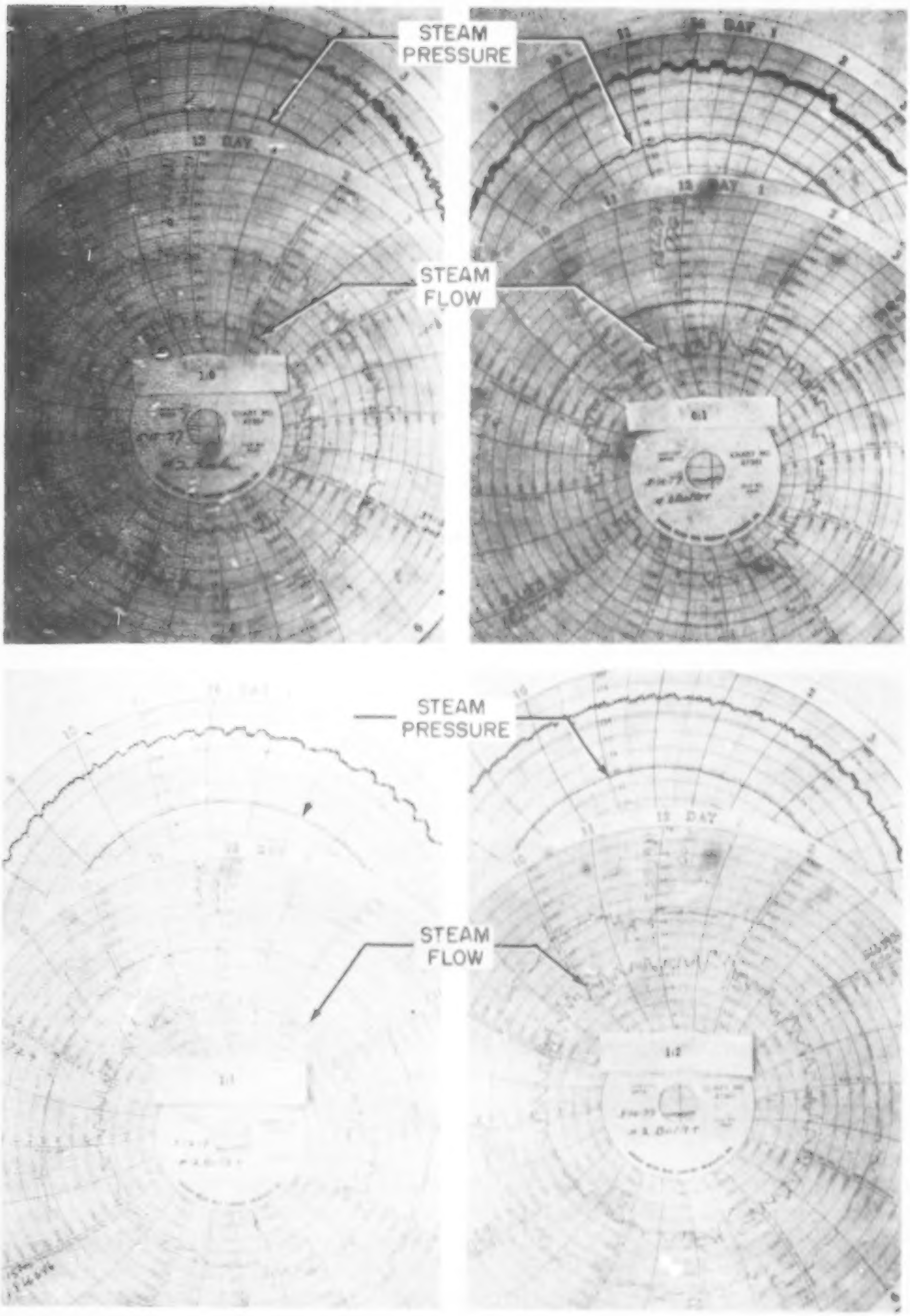


Figure 39. Pressure chart recordings for coal, blend, and dRDF firings.

When 100 percent pellets were fired, the feeders were the rate-limiting component. The 9.9-kg/sec (78,500-lb/hr) boiler could maintain 7.1 kg/sec (56,000 lb/hr) of steam per hour with 100 percent pellets and manual airflow control. When the 7.6 kg/sec (60,000-lb/hr) boiler burned 100 percent pellets while using the automatic air/fuel ratio controller, unburned fuel accumulated at the base of the rear wall, the entire fuel bed had a very sparse fire, and the steam pressure dropped 413 kPA (30 psi). This condition was due principally to high excess air levels. Because of the control system limitations, the air control could not be adequately biased downward; consequently, there was a 600 percent excess air level in the furnace. The difficulty with the boiler control was easily resolved by taking the underfire air modulation control off automatic to allow an operator to manually control the airflow and to track the steam load rather than the fuel feed rate. With the air control in the manual mode, steam pressure variations were about 14 kPa (2 psi) with the air supply fixed for 12 percent CO_2 at the peak of a load swing.

Mass and Energy Balance

Table 9 summarizes the boiler efficiency data which were calculated by the AMSE Short Form loss method. The complete forms are included in Appendix B.

TABLE 9. HEAT BALANCE SUMMARY BASED ON AS-RECEIVED FUEL

BLEND	1:0	1:1	1:2	0:1
PARAMETER				
Fraction of Rating	.17	.33	.30	.19
Excess Air (%)	104	82	99	113
LOSSES				
Dry Gas	17.9	13.7	17.8	19.4
Fuel Moisture	.1	.9	1.2	4.0
H_2O for H_2 Combustion	4.0	5.1	5.4	8.1
Combustibles in Refuse	18.3	25.3	16.6	3.0
Radiation	3.7	1.8	1.8	3.7
Unmeasured	1.5	1.5	1.5	1.5
TOTAL	45.5	48.3	44.1	39.7
EFFICIENCY	54.5	51.7	55.9	60.3

The high carbon losses in the refuse are most unusual and account for the extremely low efficiencies (normal spreader-feeder efficiencies are between 74 and 80 percent). The carbon content of the refuse (bottom ash, collector ash, and fly ash) for the various coal:dRDF blends is shown in Figures 40, 41, and 42. The carbon content of the three ash streams varied as follows: (1) bottom ash, 2 to 10 percent; (2) collector ash, 50 to 90 percent; and (3) fly ash, 30 to 40 percent.

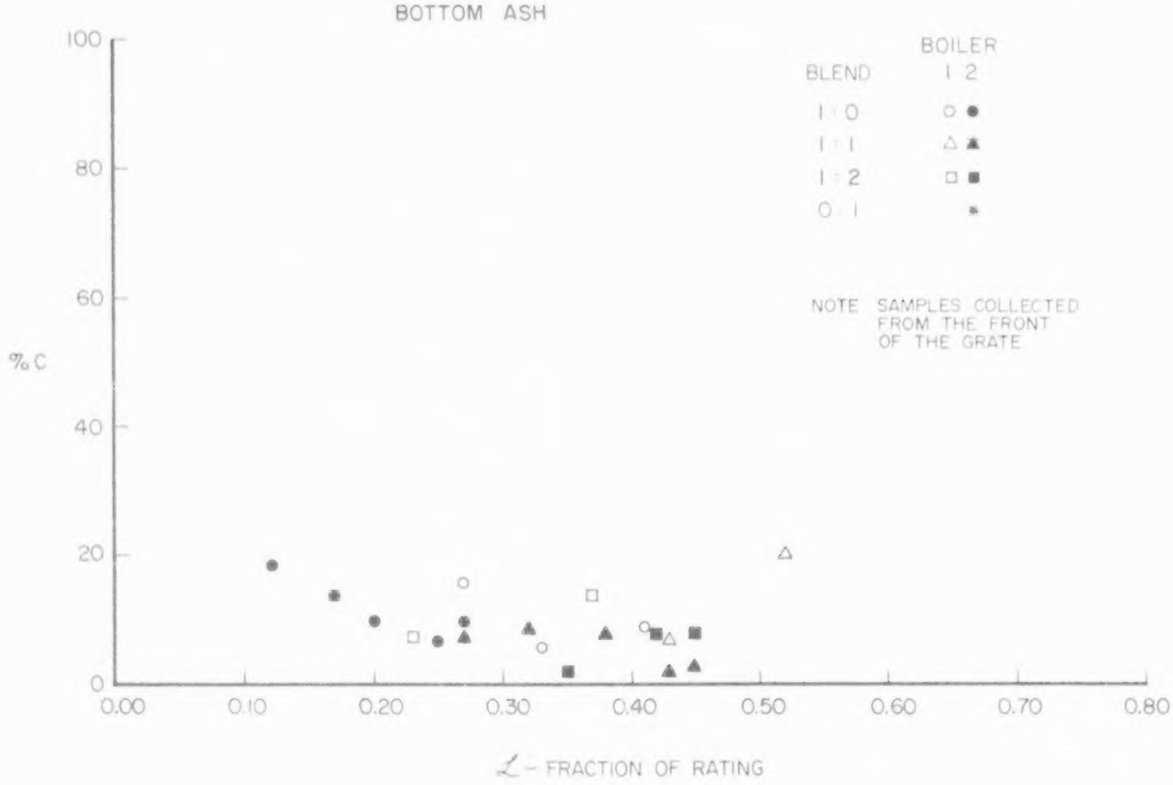


Figure 40. Effects of blend and load on carbon content of bottom ash.

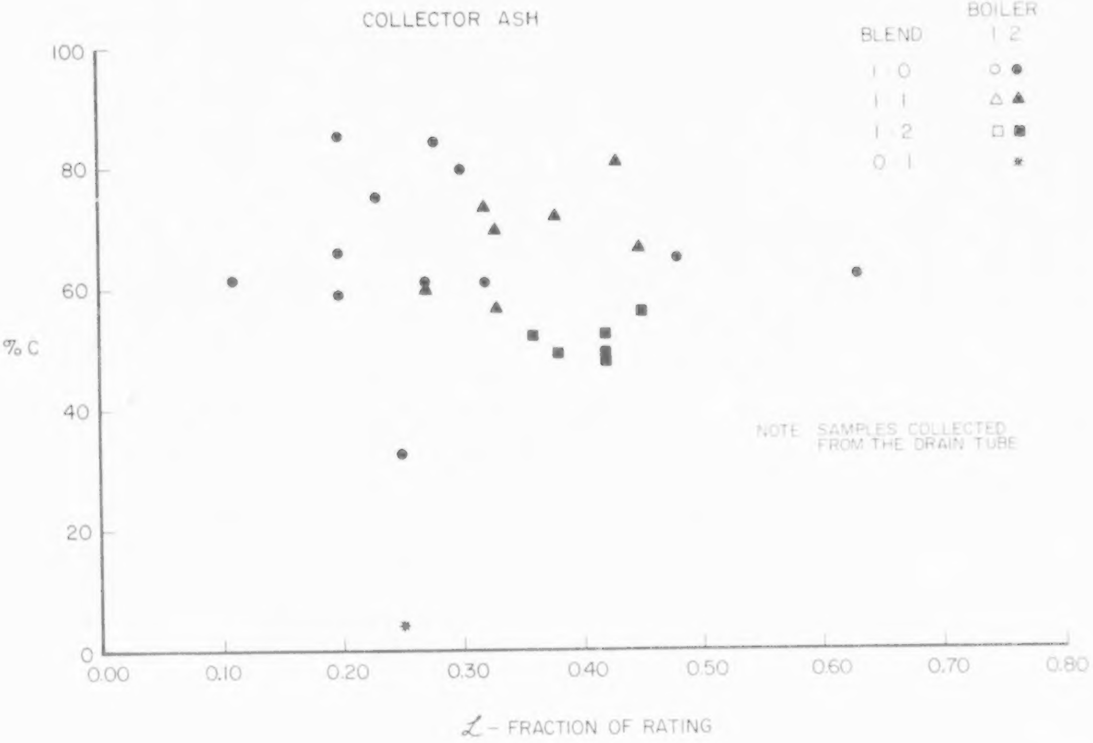


Figure 41. Effects of blend and load on carbon content of collector ash.

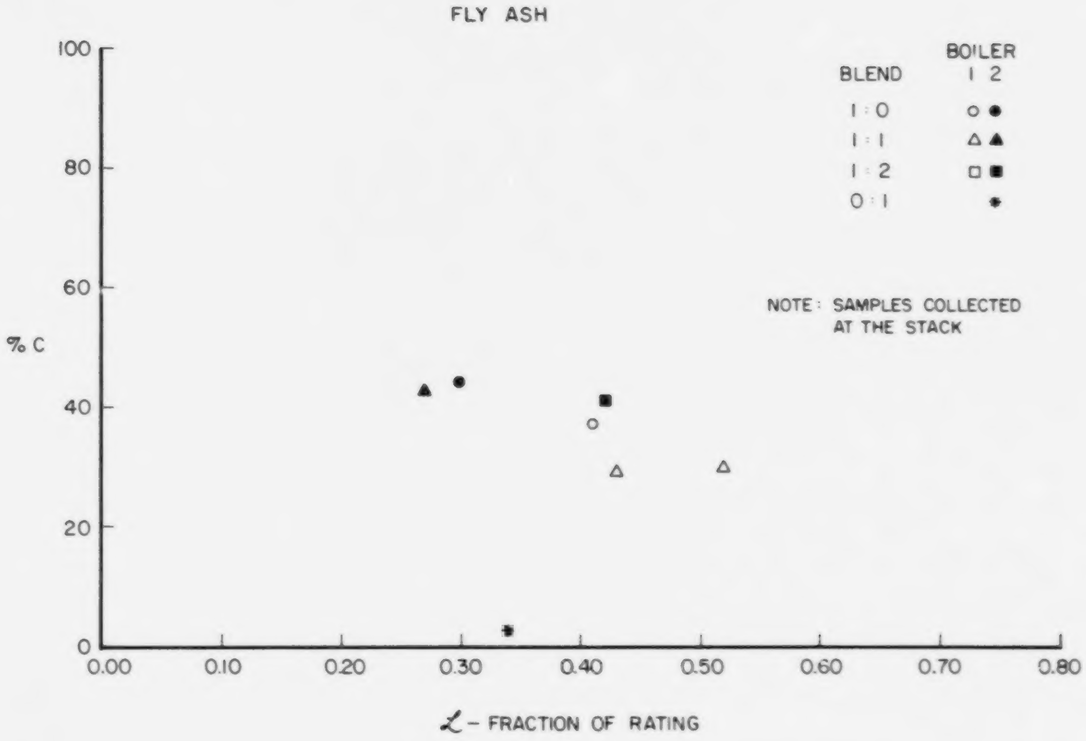


Figure 42. Effects of blend and load on carbon content of fly ash.

The mass balance for the various blends is presented in Table 10. This balance indicates that an abnormally high amount of ash was removed by the collector. Analysis of fly ash samples taken from the collector revealed that 85 to 90 percent of the particles were larger than 50 micrometers. Since collectors have much higher efficiencies for particulates in this size range, the higher collector weights may be justified. However, such an ash weight distribution is not typical of expected boiler performance.

TABLE 10. ASH MASS BALANCE

Test	Blend Coal:dRDF	Fuel Flow kg/hr	% Ash in Fuel	Ash in Fuel kg/hr	Bottom Ash kg/hr		Fly Ash kg/hr		Collector Ash* kg/hr	
					Carbon Free	With Carbon	Carbon Free	With Carbon	Carbon Free	With Carbon
May 4, 1977	1:0	872	21.9	191	82	89	5	7.7	104	219
May 13, 1977	1:1	1489	23.3	347	232	238	5	6.8	110	369
May 11, 1977	1:2	2035	23.4	476	324	341	7	10.2	145	300

* The collector weight was determined by difference.

In addition, the carbon content of the bottom ash in the various blends varied little. When the dRDF substitution was increased, the fly ash burnout was improved.

Figure 41 indicates that the carbon content of the collector ash dropped significantly when the amount of dRDF was increased in the 1:1 to the 1:2 blend firings. Since this drop effectively offsets the wet flue gases losses, the boiler efficiency did not change appreciably as more dRDF was substituted for coal. As a result, the boiler efficiency had only minor differences over the various coal:dRDF blend ratios tested. This fact is confirmed when the input/ouput efficiency data are plotted as in Figure 43. To determine the input/output efficiency, the fuel in the feed trough was run out and the steam integrator read. After the feed trough was refilled with weighed fuel, it was again emptied and the final integrator reading determined. Dividing the fuel heat content into the heat content of the steam yields the efficiency. Even though the steam meter was calibrated, the differences in efficiency when comparing those calculated by the loss method with those computed by the input/output method were significant enough to suggest a constant multiplier error in the steam meter. Hence, efficiency values are not provided in Figure 43. The input/output efficiency data shown in Figure 43 confirm the heat loss calculations in that there is no distinguishable difference in the efficiencies when firing blends or coal. This conclusion is unique to the boiler installation at MCI since the large amount of ash and unburned carbon losses attributed to the collector is certainly an anomally to expected boiler performance.

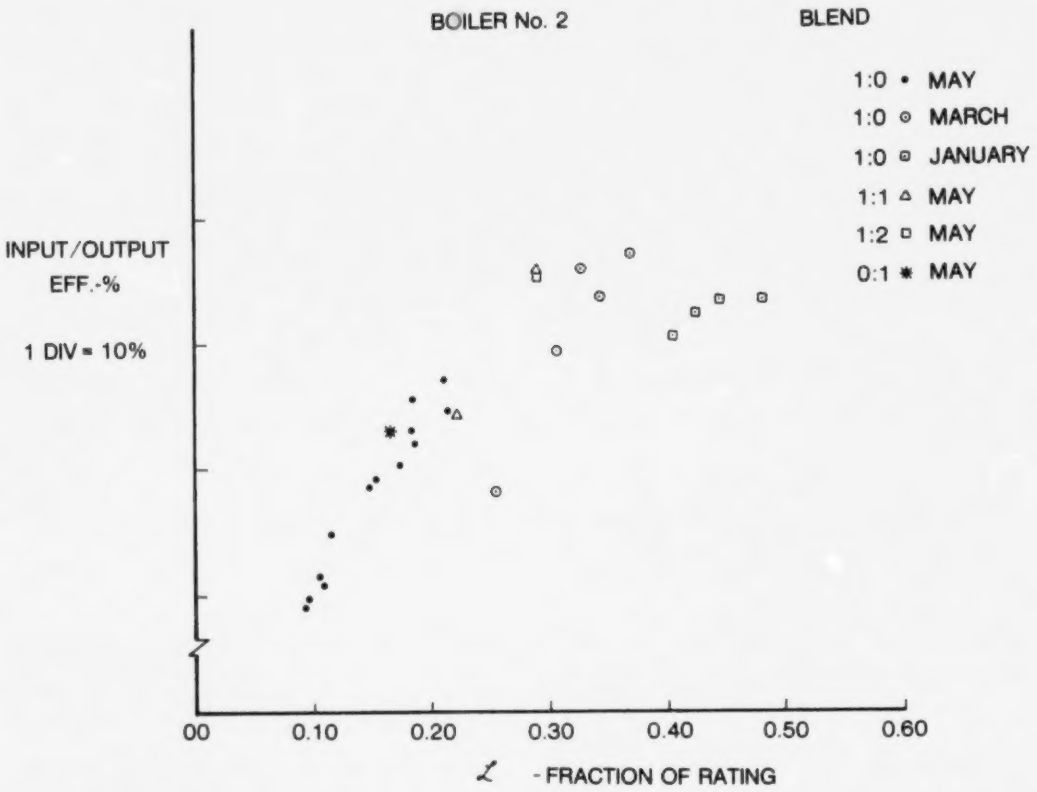


Figure 43. Effects of blend and load on input/output efficiency.

Low Load Performance

A positive result of the tests was the substantially improved low-load performance and the decreased plume opacity (indicative of better burnout) when dRDF was substituted for coal.

Normally a 3:1 or 4:1 turndown ratio on spreader-feeders is considered the practical limit to avoid severe smoking. With the use of dRDF, this turndown ratio was increased. Although of lesser importance for base-loaded industrial plants, the demonstration of the boiler's ability to operate at extremely low loads is particularly advantageous for heating plants and institutional facilities which must support a very small summer base load yet have sufficient capacity to meet severe winter heating requirements.

SUMMARY

The Hagerstown experience has increased the knowledge of blend behavior in a spreader-feeder. The fuel entered the furnace satisfactorily, burned well, and met plant energy requirements. The operative and control discrepancies were all corrected by simple adjustments. Some biasing of the air controls was required to prevent slagging on the fuel bed during load sheds. The only other limitations on the boiler operation occurred when the boiler was operated on 100 percent dRDF. During this test both the spreader and the ash handling systems became capacity-limited.

Proper adjustment of the spreader-feeders is critical to prevent slagging and fouling. Some slagging and fouling occurred (in excess of what would occur when firing with coal only) on the walls slightly above the grates but was readily removed. The corrosion experiment resulted in wastage comparable to what might be expected for coal-only firing. This test was too short in duration, however, to permit any definite conclusions on material wastage.

While the boiler performance when firing coal:dRDF blends up to 1:2 (by volume) was generally similar to that when firing coal only, final conclusions must await further long-term demonstration testing in which boiler loads can be established at rated capacity and satisfactory boiler operating characteristics can be maintained.

A follow-on demonstration test is currently scheduled to be carried out in a spreader-feeder fired boiler with a rated capacity of 18.9 kg/sec (150,000 lb/hr) and superheat capability.

SECTION 5

ENVIRONMENTAL PERFORMANCE

INTRODUCTION

If a boiler plant can comply with emission regulations when firing coal, the question arises whether it can still do so when substituting dRDF for some of the coal. The low sulfur content of the dRDF could degrade precipitator performance which, when coupled with the high ash content of dRDF, could result in the emissions exceeding the regulation limits. Also, the high chlorine content of the dRDF raises concern about the long-term corrosion effects on the boiler system.

To answer this question, the current study assessed changes in emissions as dRDF was substituted for coal. Although the quantitative results for the coal:dRDF emissions are significant, the principal conclusions are drawn by comparing the coal:dRDF blend emissions with coal-only emissions. Therefore, base lines were established before and after each blend run by duplicating all test conditions for coal-only firing.

This section discusses the method of sampling and data analysis. It also covers the impact of substituting dRDF for coal on particulate emissions, gaseous emissions, and trace compound emissions in the order given.

FIELD SAMPLING SETUP

Since at least four 2-week tests were to be conducted at the Hagerstown plant, a weatherproofed test shed enclosed in sheet metal and readily accessible to the stack on two sides (see Figure 44) was constructed for the environmental testing. Placed 4.9 m (16 ft) above the roof line, the shed encompassed one quarter of the single stack that served all three boilers. Four 0.1-m (4-in.) half couplings were installed in the stack to serve as sampling ports, two on the north side and the other two on the west side, with each pair arranged vertically with a 0.61-m (2-ft) separation. A stairwell from the plant catwalk system provided access to the shed. A transmissometer was installed in another pair of ports spanning the stack on the north-south axis at about 0.9 m (3 ft) above the roof line and 4.6 m (15 ft) below the other sampling ports.

One port in the stack was used to insert a sintered steel filter through which stack gas samples were extracted, cooled in a condenser/knockout box, and piped through heated umbilicals to SYSTECH's sample analysis trailer. This trailer housed facilities for wet chemistry analyses. In the trailer, the samples were distributed through a manifold to provide flue gas to the

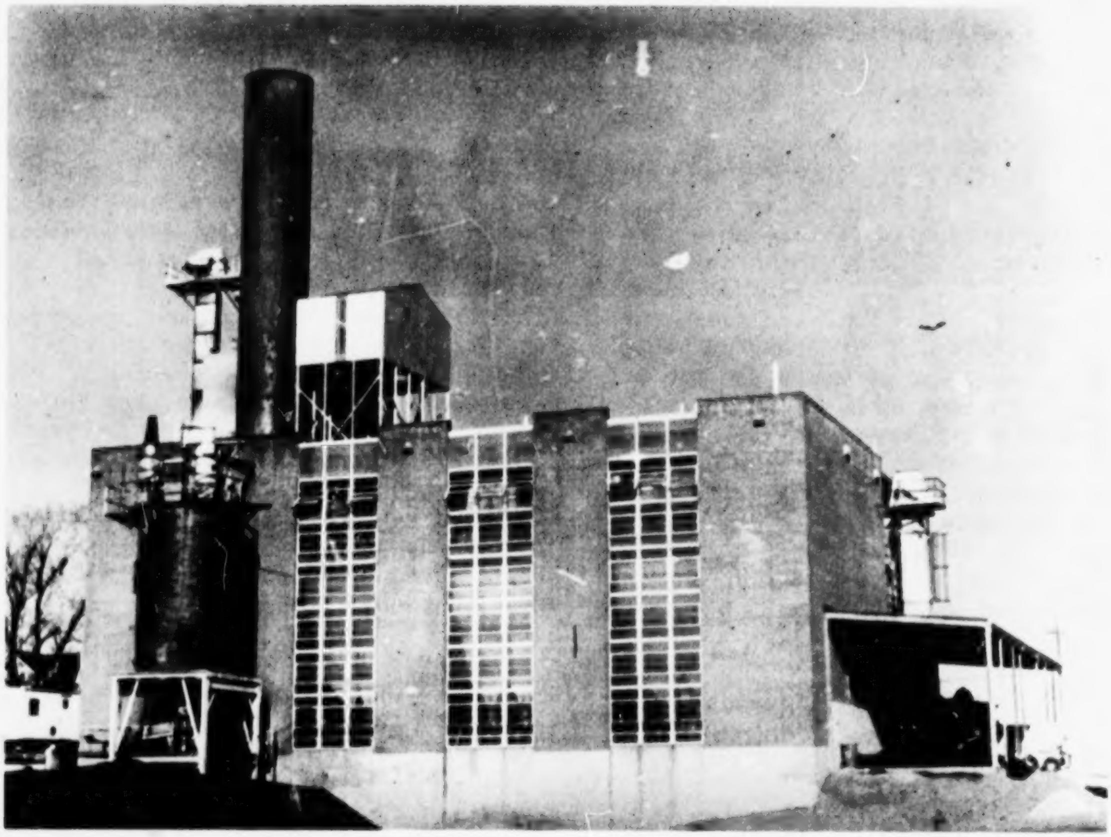


Figure 44. View of MCI power plant showing stack sampling shed and temporary fuel handling system at right.

gas analyzers. A Theta Sensor, Inc., trigas analyzer was used for continuous oxygen, nitrogen dioxide, and sulfur dioxide measurements. A slip steam was also distributed to an AID gas chromatograph to determine both total hydrocarbons and the composition of hydrocarbons lighter than C_6. The manifold was also used to distribute calibration gases.

Another sampling port was used to insert a 1/4-inch-diameter steel pipe into the center line of the boiler outlet. The pipe was connected with copper tubing to an Orsat analyzer located on the boiler house floor. This sample system was used to determine the characteristics of the flue gas leaving the boiler. Figure 45 illustrates the overall arrangement of the boilers, breeching, and locations where the various ash, fuel, and flue gas samples were taken.

TEST CHRONOLOGY AND PROCEDURES

Table 11 illustrates the test chronology for the entire program. The consumption of dRDF throughout the program was 20.9 Mg (23 tons) in December, 106.1 Mg (117 tons) in March, and 127.9 Mg (141 tons) in May for a grand total of 254.9 Mg (281 tons). During the May test, Boiler No. 2 was continuously fired with coal:dRDF blends for 132 hours. The test time breakdown for the blend firings was 58 hours for the 1:1 blend, 53 hours for the 1:2 blend, and 29 hours for the 0:1 blend (100 percent dRDF). The table lists the fraction of the boiler load rating, the coal:dRDF ratio, and the number of emission data measurements for each test blend. The test program was designed so that three sets of emissions data would be acquired for each test blend. While good boiler testing practices would dictate that the boiler be stabilized for 24 hours on each blend before collecting emissions data, the limited supply of dRDF necessitated that the stabilization period be limited to overnight (approximately 12 to 15 hours). Each test blend was subjected to the following battery of emission tests:

3 each - EPA Method 5 - Particulate mass flux, Cl, F, SO_2, SO_3, and trace organic and inorganic compounds

3 each - Cascade Impactors - Particulate size distribution

2 each - EPA Method 7 - Nitrous oxides

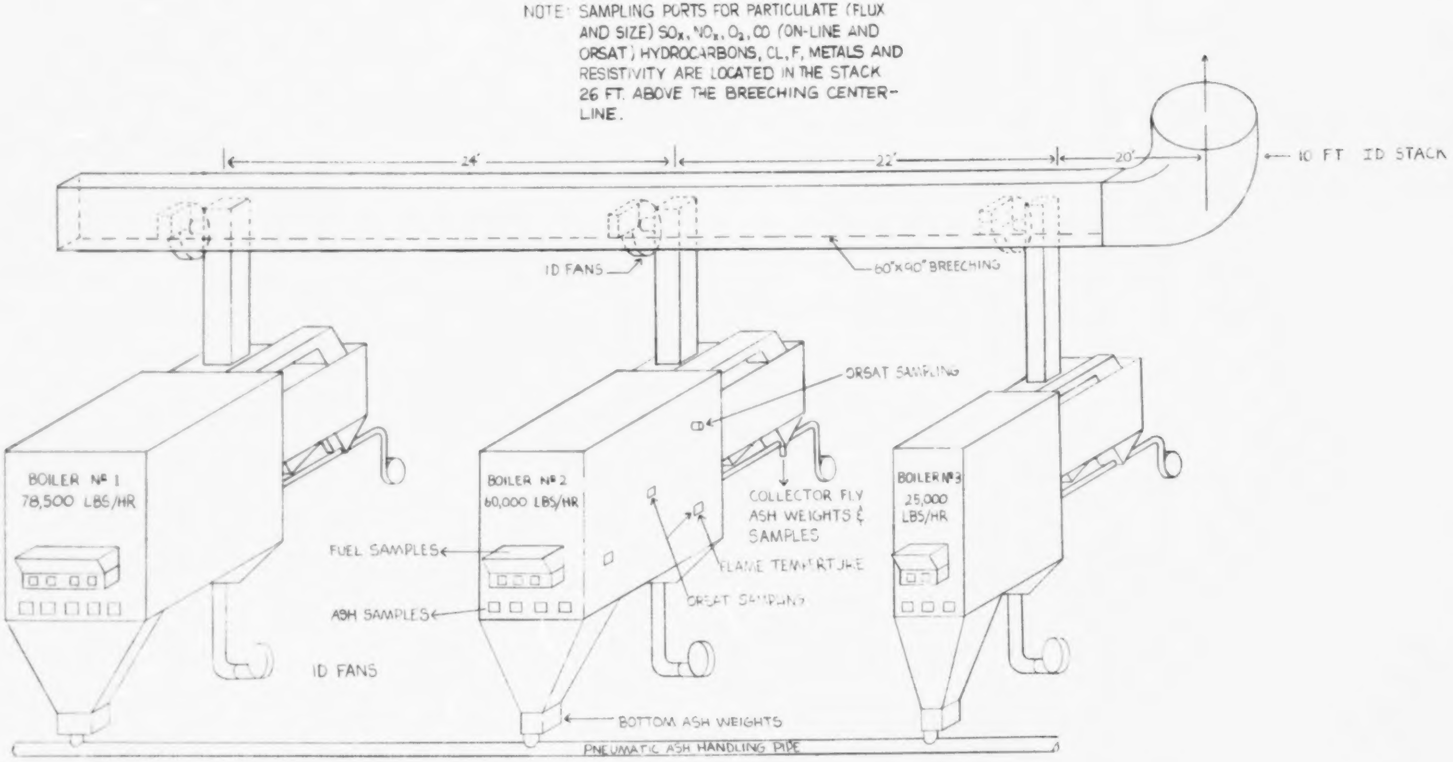
6 each - Orsat - CO_2, O_2, and CO

8 each - Orsat - CO_2

4 each - AID Gas Chromatograph - Total hydrocarbons

4 each - Wahlco Probe - Resistivity

1 each - Tedlar Bag - Record sample



NOTE: SAMPLING PORTS FOR PARTICULATE (FLUX AND SIZE) SO_x, NO_x, O_2, CO (ON-LINE AND ORSAT) HYDROCARBONS, CL, F, METALS AND RESISTIVITY ARE LOCATED IN THE STACK 26 FT. ABOVE THE BREECHING CENTER-LINE.
24'
22'
20'
10 FT ID STACK
ID FANS
60"x90" BREECHING
ORSAT SAMPLING
BOILER Nº 1
78,500 LBS/HR
BOILER Nº 2
60,000 LBS/HR
BOILER Nº3
25,000 LBS/HR
COLLECTOR FLY ASH WEIGHTS & SAMPLES
FUEL SAMPLES
FLAME TEMPERTURE
ASH SAMPLES
ORSAT SAMPLING
ID FANS
BOTTOM ASH WEIGHTS
PNEUMATIC ASH HANDLING PIPE

Figure 45. Layout of Boilers No. 1, 2, and 3 with sampling locations indicated.

TABLE 11. CHRONOLOGICAL LISTING OF TEST CONDITIONS

	Date	Boiler No.	Boiler Load Fraction of Rating	Blend	Data Replication
#1	12/8/76	1	.45	1:1	1
	12/10	1		1:0	2
	12/13	1	.45	1:1	2
	12/14	1	.43	1:1	2
#2	1/20/77	1	.53	1:0	2
	1/21	1	.47	1:0	1
	1/24	1	.53	1:0	1
	1/25	1	.50	1:0	1
#3	3/19	1	.51	1:0	2
	3/21	2	.40	1:0	2
	3/22	1	.40	1:0	1
	3/23	1	.43	1:1	2
	3/24	1	.44	1:1	1
	3/28	1	.38	1:0	1
	3/29	1	.36	1:2	2
	3/30	1	.26	1:2	1
	3/31	1	.27	1:0	2
#4	4/1	1	.35	1:0	1
	5/3	2	.25	1:0	1
	5/4	2	.20/.22	1:0	2
	5/5	2	.31/.51	1:0	2
	5/10	2	.36/.30	1:2	2
	5/11	2	.36/.34	1:2	2
	5/12	2	.34/.28	1:1	2
	5/13	2	.39/.30	1:1	2
	5/14	2	.27/.26	0:1	2
	5/16	2	.21/.36	1:0	2
	5/17	2	.17	1:0	2

Note: Boiler No. 1 is rated at 9.9 kg/sec (78,500 lb/hr) and
Boiler No. 2 is rated at 7.6 kg/sec (60,000 lb.hr).

Continuous - Theta Sensors, Inc. - CO_2, SO_2, and NO_2
Trigas Meter

Continuous - Leads & Northrup - Opacity
Transmissometer

As Req'd - Draeger Tubes - CO, CO_2, and SO_x

The Battelle Tenex traps were only run three times throughout the test, i.e., at 1:0, 1:1, and 1:2 test blends. When the measured emissions produced unusual results, the Tedlar bag sample was used to further clarify the data through gas-chromatograph analysis.

The Draeger tubes were used periodically throughout the program whenever a quick, approximate concentration of a particular pollutant gas was desired.

The following paragraphs detail the test procedures for collecting, monitoring, and analyzing each emission.

Opacity

Opacity was measured by a Leads & Northrup single-pass transmissometer spanning the stack and calibrated with neutral density filters. The transmissometer was calibrated with the neutral density filters by installing the unit in a pipe section whose length was equivalent to the stack diameter.

Particle Mass Flux

The particle mass flux was measured by an EPA Method 5 train, which is schematically illustrated in Figure 46. Because of the low gas flow rates, nominal 12.7-mm (1/2-in.) nozzles were installed to produce nominal 0.0047-m^3/sec (1-cfm) flow rates through Greenburg-Smith impingers. The 3-m (10-ft) diameter stack was traversed from two sides by a single 3.7-m (12-ft) stainless steel probe.

The stack was sized for acceptable flow rates with all three boilers operating simultaneously. During testing, however, only a single boiler was on line at part load. Consequently, the velocity of the stack gases was less than 2.1 m/sec (7 ft/sec) which is below the detection limit of an S-type pitot tube. Although sophisticated velocity monitoring equipment was considered, the large quantities of dust made its application inappropriate. As an alternative method for measuring the flow rates, the flue gas composition at the stack, the boiler load and efficiency, and the ultimate analysis of the fuel were used to calculate the velocity. The mathematics relating these parameters and the apparent pitot reading are presented in Appendix C.

Because of the velocity conditions at the stack, the extent of anisokineticism could not be determined precisely. In any event, the error due to anisokinetic sampling in these experiments is likely negligible because of

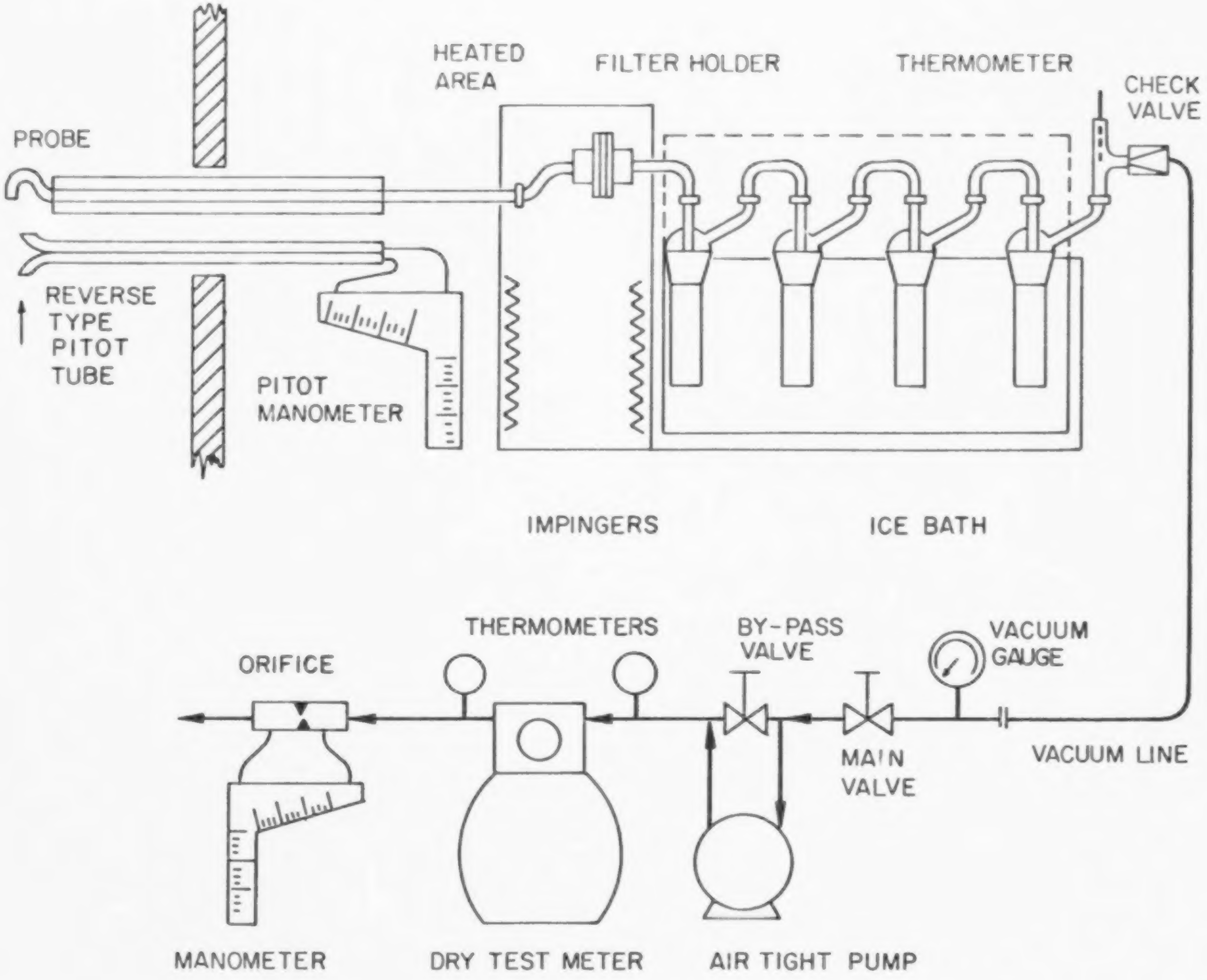

PROBE
HEATED AREA
FILTER HOLDER
THERMOMETER
CHECK VALVE
REVERSE TYPE PITOT TUBE
PITOT MANOMETER
IMPINGERS
ICE BATH
THERMOMETERS
BY-PASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
VACUUM LINE
MANOMETER
DRY TEST METER
AIR TIGHT PUMP

Figure 46. Schematic of EPA Method 5 sampling train setup.

the fine particle sizes and low gas velocities.[3] As a general rule, when an aerosol is less than 5 micrometers in diameter, there is no need for isokinetic sampling. At Hagerstown, approximately 65 percent of the particulates were less than 5 micrometers. In view of the large amount of less than 5-micrometer-diameter particulates present in the flue gas and the utilization of a calculated stack velocity, the particulate emissions should be representative of actual plant operation.

Size Distribution

The size distribution of the aerosol emitted from the Hagerstown plant was monitored in the stack downstream of the multiclone collectors. All measurements were made with an MRI cascade impactor which was operated according to the manufacturer's recommendations. The method of forming a nonrebounding substrate for the impactor plates was developed at SYSTECH according to other researchers' experience with the MRI cascade impactor. After the impactor plates were dipped in benzene in which Apiezon-H grease was dispersed, they were baked overnight at 232°C (450°F). The resulting coating was extremely uniform. "Blank" test runs were performed in which the MRI cascade impactor was inserted in the stack with a filter installed before the impactor. These tests confirmed that the coating on the impaction disks did not come off on the O-rings or during handling. The substrate forming method, therefore, proved to be an acceptable procedure. Consistent particle size distributions, as shown on the stages in Figure 47, further substantiate the validity of this method.

The MRI cascade impactor was always inserted 1.5 m (5 ft) in from the west side wall. After the impactor was heated, it was connected to the train shown in Figure 48, checked, and inserted into the stack. When the sampling was completed, the impactor was removed from the stack and disassembled. The impactor plates were placed in tared petri dishes. After the plates were returned to the laboratory for final weighing in a clean environment, the net weight gain per stage was used to determine the cumulative mass distribution. The characteristic aerosol diameter of each stage was obtained from the factory-supplied calibration curves for the test conditions and unit density aerosols.

Fly Ash Resistivity

The particle resistivities were measured on site with a WAHLCO probe. A sketch of this probe is shown in Figure 49. Dust samples were cyclonically captured from the stack gases in a collector cup. The captured particles collectively became a resistor between electrodes A and B. After a constant voltage was applied to the electrodes and the current flow was measured, the resistivity was computed by substituting the voltage and current values in

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[3] Watson, H. H. American Hygiene Association Quarterly, Volume 15 1954. p. 21.

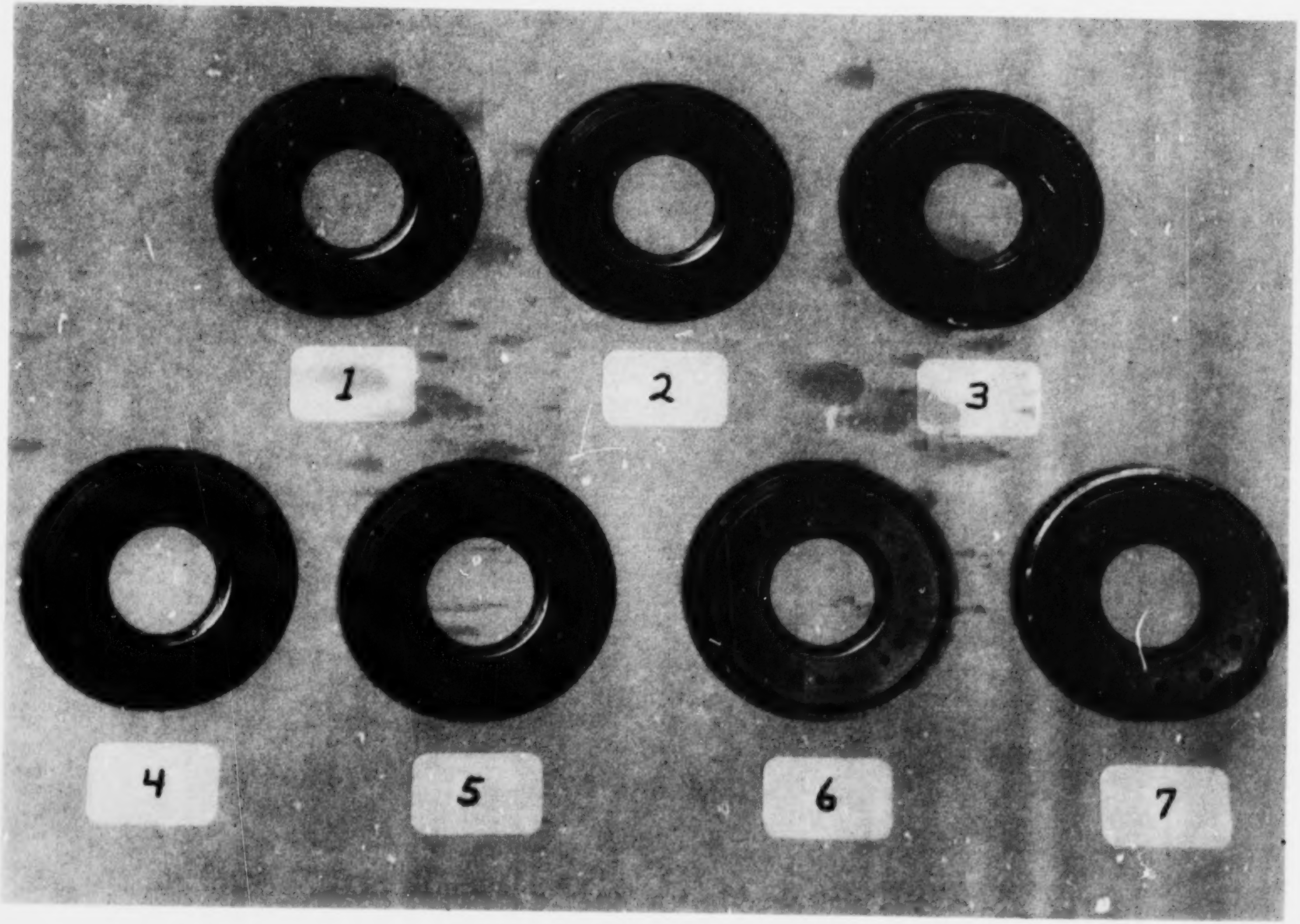

Figure 47. Typical dust loading of MRI cascade impactor stages during 1:1 blend firing.

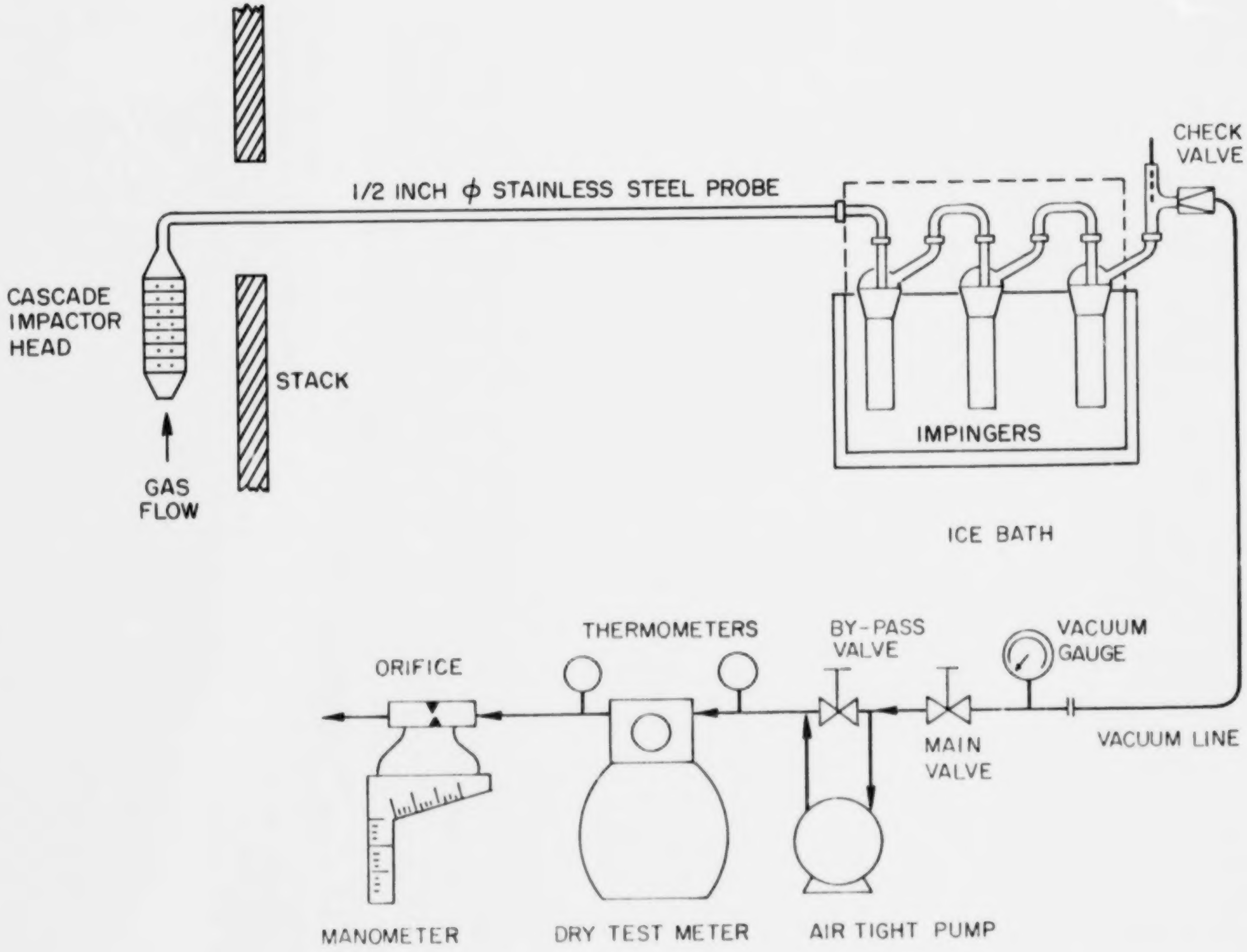
CHECK VALVE
1/2 INCH ϕ STAINLESS STEEL PROBE
CASCADE IMPACTOR HEAD
STACK
GAS FLOW
IMPINGERS
ICE BATH
THERMOMETERS
BY-PASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
VACUUM LINE
MANOMETER
DRY TEST METER
AIR TIGHT PUMP

Figure 48. Schematic of MRI cascade impactor sampling train setup.

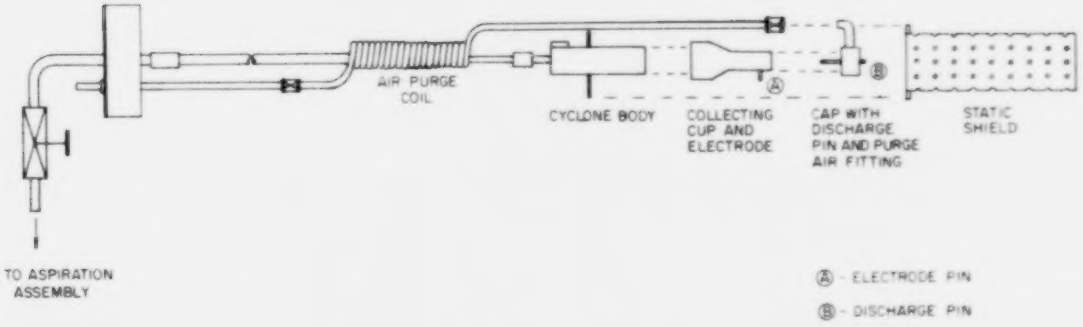
AIR PURGE COIL
CYCLONE BODY
COLLECTING CUP AND ELECTRODE
CAP WITH DISCHARGE PIN AND PURGE AIR FITTING
STATIC SHIELD
Ⓐ
Ⓑ
TO ASPIRATION ASSEMBLY
Ⓐ - ELECTRODE PIN
Ⓑ - DISCHARGE PIN

Figure 49. Schematic of WAHLCO resistivity probe assembly.

Equation 5.1. Particle resistivities were continuously checked through the blend and coal-only tests.

$$\text{Resistivity} = (\text{voltage}/\text{current})\ L \qquad (5.1)$$

where L = constant

SO_2

Sulfur dioxide levels in the flue gas were determined by two different techniques. With one technique, SO_2 levels were continuously monitored by a trigas meter manufactured by Theta Sensor, Inc. This electro-chemical sensor was calibrated with standard SO_2 gases. With the second technique, wet chemistry determinations were made by analyzing the sulfur level in the first impinger of the EPA Method 5 train. A 10 percent hydrogen peroxide/water solution in the impinger was titrated with barium perchlorate to yield a measure of the SO_x in the flue gas. Both samples were collected at the same location; i.e., the stack. When the results from the two techniques were cross correlated, the corresponding values proved to be similar. Since the SO_3 concentration is an order of magnitude less than the SO_2 concentration in a flue gas stream, this cross correlation was considered to be valid.

Oxides of Nitrogen

The emissions of oxides of nitrogen were determined by two different techniques. In one technique, the Theta Sensor trigas monitor was employed and in the second, an EPA Method 7, a phenol disulphonic test method, was used.

Halogens

During each particulate mass flux evaluation, the halogen emissions were simultaneously determined by replacing the water in the first impinger in the EPA Method 5 train with a 10 percent hydrogen peroxide solution. After the Method 5 testing was completed, the first impinger was then analyzed for chlorine and fluorine by using specific ion electrodes.

Oxygen

In addition to monitoring SO_x and NO_x, the Theta Sensor trigas monitor had the capability of continously monitoring oxygen. All three of these parameters were continuously recorded on a strip chart. Standard calibration gases were used to calibrate the instrument at the beginning and end of each test day. In addition, Orsat readings were taken at the stack, and the O_2 readings were cross correlated with the O_2 readings on the Theta Sensor trigas monitor. Identical readings verified the integrity of the sampling line.

Hydrocarbons

To determine the emissions of hydrocarbons from the Hagerstown plant, continuous gas samples extracted from the stack were passed through a sintered steel filter, a condenser knockout box, and a heated umbilical to the SYSTECH trailer where they were analyzed in the AID flame ionization detector-equipped, field-portable gas chromatograph. This instrument was operated in the totalizing mode and calibrated with a methane gas. Consequently, the total hydrocarbons are expressed in terms of a methane equivalent. The gas samples were fractionalized with a molecular sieve column capable of distinguishing between various hydrocarbons lighter than C_6.

Trace Organic Emissions

The trace organic emissions were collected by a Battelle Tenex sampler. Figure 50 illustrates how the sampler was connected after the filter in the EPA Method 5 train. The sampler was maintained at 50°C (122°F) by a recirculating water bath. After the samples were taken, the probe washes, filters, and Tenex traps were all preserved and sent to the Battelle Columbus Laboratories for analysis.

Trace Inorganic Emissions

The inorganic compounds emitted from a boiler can be in either the aerosol or the gaseous phase. To quantify these emissions, SYSTECH modified the standard EPA Method 5 train so that while the train used the normal hardware, the first impinger was loaded with a 10 percent hydrogen peroxide

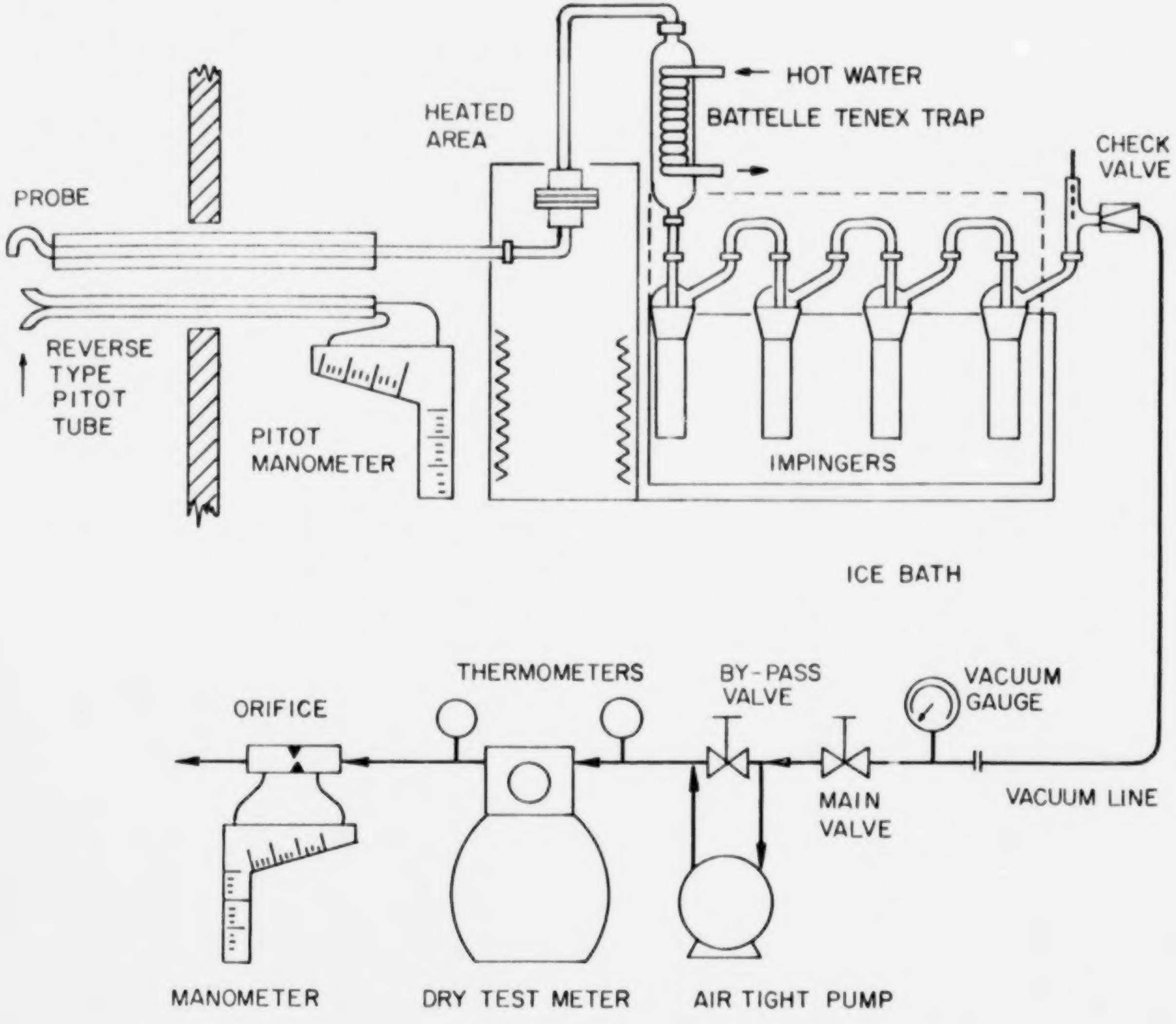
PROBE
REVERSE TYPE PITOT TUBE
PITOT MANOMETER
HEATED AREA
HOT WATER
BATTELLE TENEX TRAP
CHECK VALVE
IMPINGERS
ICE BATH
THERMOMETERS
BY-PASS VALVE
VACUUM GAUGE
ORIFICE
MAIN VALVE
VACUUM LINE
MANOMETER
DRY TEST METER
AIR TIGHT PUMP

Figure 50. Schematic of Battelle Tenex sampling train setup.

solution, and the next two impingers were charged with a catalyzed ammonia persulfate reagent. These impinger solutions were used to ensure the capture of the gas phase metals.

The probe washings, filters, and impinger solutions were all analyzed in SYSTECH's laboratories by using atomic absorption spectrometry with appropriate detectors and furnaces. Each filter was cut in half, dryed, and desiccated. The half to be digested was then weighed for total particulate. The remaining half was retained for voucher or repeat analysis. One to two mℓ of concentrated HNO_3 were added to each filter and dried slowly on a heated steam table. The filters were not dried completely to avoid losing volatile metals such as Pb. Additional HNO_3 was then added to cover the sample. The sample was refluxed until the digestion was complete. The reflux was removed from heat, and after the sample had cooled, concentrated HCl was added until the sample was in solution. After the sample was filtered, the filtrate was brought to a known volume for atomic absorption analysis. Filter blanks were analyzed along with the samples to provide supporting data.

Fly ash samples were dried, desiccated, and then halved and quartered to obtain a representative 2-g sample. The bottom ash samples were ground up to a minimum sieve size in a Wiley mill; then the ground samples were halved and quartered, and a 2-g aliquot was taken for analysis. These samples were digested by the same procedure as previously described for the filters. With the high silica content, it was difficult to dissolve the entire sample. Consequently, the digestion was considered complete when the sample had a straw-like color after a minimum of 2 to 3 hours of refluxing.

For the Hg analysis, a separate digestion was necessary. Each sample was weighed and put into a BOD bottle. The procedure for analyzing Hg required a persulfate digestion as described in EPA Manual of Methods for Chemical Analysis of Water and Wastes. All samples were analyzed in duplicate.

DATA ANALYSIS AND NORMALIZATION

Data Analysis

The data management and interpretation was complicated by the test program and load limitations; for example, only one boiler would be on line at a time. Since the single on-line boiler had to follow a modulating steam load, the test matrix had to include the steam load as a variable. Consequently, data were taken at various load points as the boiler met the varying steam needs.

Since soot formation, flame temperature, boiler efficiency, hydrocarbon emissions, etc., are all functions of the boiler firing rate, all data were analyzed as a function of the boiler rating to minimize the effect of testing in two different size boilers. Because of the limited number of data points and the similarity of the data taken on Boilers No. 1 and 2, all data were combined.

A method of data interpretation different from usual techniques had to be employed to identify the effect of substituting dRDF for different test coals with varying coal chemistries. The selected method was based on the principle of establishing the range of likely values for the reference parameter and then applying that range to the dependent parameters to ensure meaningful results.[4] Accordingly, with this method a regression analysis was conducted with 90 percent confidence intervals for the best fit lines based on the coal-only (1:0) data set. Figure 51 illustrates the principle. After the data for two different blends were independently regressed and the confidence interval of the regression line for the first data set (A) was established, the two data sets could not be called different if the regression line for the second data set (B) was within this interval. However, if the regression line for the second data set (C) was where it would be outside this interval, the two data sets could be called different.

Because of the marked disparity in the number of data points for the 1:0 and 0:1 blend tests (25 versus 2 data points), the slope of the 1:0 blend data as a function of load was used as the slope for all other emissions data graphically presented in this report. A t-test procedure described by Natrella[5] was used to confirm the reasonableness of this approximation. Results of this analysis indicated that at the 90 percent confidence level, the slopes of the 1:0 and 1:1 data sets would not be considered different. In fact, even though sloped lines are shown for each blend (based on the 1:0 data), a horizontal line (slope = 0) might also fit the data. The 1:1, 1:2, and 0:1 data (designated as m:n) were fit with the 1:0 slope by realizing that for the least squared error under the common slope constraint the following is true:

$$Y_{m:n} = A_{m:n} + B_{1:0}X$$

and

$$A_{m:n} = \overline{Y}_{m:n} - B_{1:0}\overline{X} \tag{5.2}$$

where $\overline{Y}$ and $\overline{X}$ are the average values of the emission and load measurements, respectively.

Data Normalization

Since the excess air levels varied throughout the testing, all results were adjusted to a common reference to remove the dilution effect. Accordingly, Equation 5.3 was used to adjust all emissions to the 50 percent excess air level.

$$X_2 = X_1\left(\frac{1 + EA_1}{1 + EA_2}\right) = X_1\left(\frac{CO_{2_2}}{CO_{2_1}}\right) \tag{5.3}$$

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[4] Murphy, T. D., Jr. Design and Analysis of Industrial Experiments. Chemical Engineering, June 1977. pp. 169-182.

[5] Natrella, M. G. Experimental Statistics. National Bureau of Standard Handbook 91. U.S. Government Printing Office, Washington, D.C., 1963.

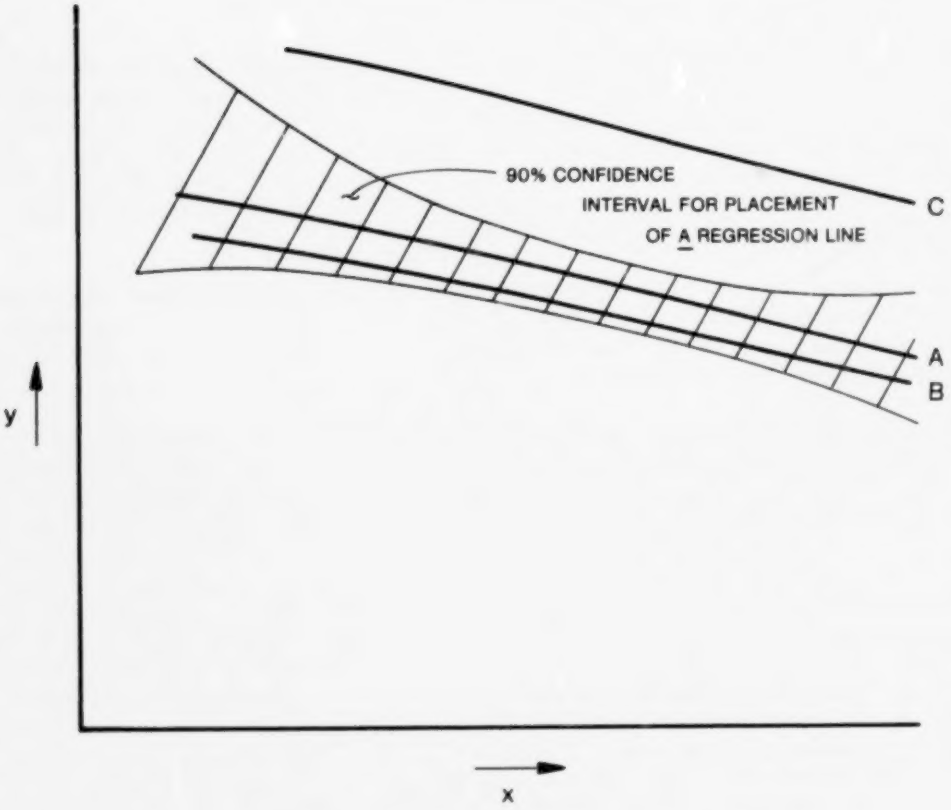
90% CONFIDENCE
INTERVAL FOR PLACEMENT
OF A REGRESSION LINE
C
A
B
y
x

Figure 51. Graphic representation of probably similar (A & B) and potentially dissimilar (A & C) regression lines through data set.

where X_2 = emission level corrected to 50 percent excess air

X_1 = measured emission level at test conditions

CO_{2_2} = carbon dioxide level at 50 percent excess air as calculated from fuel properties and stoichiometry

CO_{2_1} = measured carbon dioxide levels at test conditions

$(1 + EA)$ = stoichmetric air plus excess air

Since carbon dioxide levels are direct measurements that correlate fairly well with excess air levels, the carbon dioxide levels were used for all adjustments. The expected carbon dioxide level at 50 percent excess air can be determined from stoichiometry by using the fuel property data. The reference carbon dioxide levels for all coal:dRDF blend and dRDF-only tests in March were 12.2, 12.6, and 12.3 percent. These percentages correlate with the 1:1, 1:2, and 0:1 blends, respectively.

The experiment was further complicated by varying fuel properties when different coals and dRDF supplies were used. The ultimate and proximate analysis for coal and dRDF shown in Tables 3 and 4 reflects the varying fuel properties during the test period.

To facilitate detection of the emission changes when the coal:dRDF ratio was varied, the fuel properties of the different coal and dRDF supplies were normalized by using the properties for the coal delivered for the March tests and the properties for the average composition of dRDF delivered for all tests.

Emissions were normalized by dividing the fraction of each element in the fuel per joule equivalent by the amount of that element in the reference fuel. This correction assumes that a constant fraction of sulfur, for example, is emitted as SO_x regardless of the actual percentage of sulfur in the fuel. While this correction ignores secondary effects such as the sulfur chemically bound with the ash, it compensates for primary effects. The correction factors for particulates, SO_x, NO_x,* and Cl are tabulated in Table 12. The primary reduced data in Tables A-1 through A-4 of Appendix A were multiplied by the appropriate factors in Table A-5 before the statistical analysis or plotting. The fluorine, opacity, and hydrocarbon emissions were not corrected to the normalized fuel properties because either the requisite data was not available (fluorine is not measured in an ultimate analysis) or the controlling parameter was uncertain.

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*The validity of correcting NO_x organically bound nitrogen was questionable since the NO formation was governed by combustion and flame cooling rates, excess air levels, point of air addition, and recirculation effects as well as fuel nitrogen. Because of the low volumetric heat release rates encountered and high excess air levels, the NO formation for this test should have been governed by the fuel nitrogen only.

TABLE 12. FUEL ELEMENTAL COMPOSITION NORMALIZATION FACTORS FOR ADJUSTING EMISSIONS TO A STANDARD FUEL

Blend	S	Cl	Ash	N_2
December/January				
1:0	.73	.40	.72	1.03
1:1	.51	.72	1.14	1.35
March				
1:0	1.00	1.00	1.00	1.00
1:1	1.00	.90	.99	1.03
1:2	1.01	.93	.99	1.06
May				
1:0	1.23	2.00	.42	1.04
1:1	1.22	1.20	.56	.93
1:2	1.20	1.09	.62	.87
0:1	1.00	1.00	.77	.56

Element columns: S, Cl, Ash, N_2

PARTICULATE EMISSIONS TEST RESULTS

In the framework of compliance with emission regulations, the blend effects on opacity, particulate concentration, size distribution, fly ash resistivity, and overall ESP performance were evaluated. The following sections discuss these effects in the order given.

Opacity

Figure 52 shows the opacity readings averaged over 8-hour test intervals as a function of boiler load and coal:dRDF blend. The comparison of the confidence interval about the coal-only regression line with the best fit curves for the 1:1, 1:2, and 0:1 firings indicates that the overall opacity was reduced as the dRDF substitution was increased.

Because of the large diameter of the stack relative to the amount of gas discharged, the opacity appeared lower to ground-level observers than the meter reading indicated. As the plume left the stack, it was lazy, and it immediately fanned. While the opacity meter spanned a 3-m (10-ft) path, a ground-level observer could see only about a 0.3-m (1-ft) path. To adjust the measured data to indicate the opacity which would be seen in a more closely sized stack (4 feet versus the actual 10 feet), a second scale was included on Figure 52. Beer's Law was used to apply the path length correction to the measured light attenuation. Equation 5.4 is the form of Beer's Law which governs the transmittance of light across an attenuated gap.

$$I = I_0 \mathrm{EXP}\ (-KL) \qquad (5.4)$$

and

$$0 \equiv 1 - I/I_0$$

where I = perceived source intensity
I_0 = source intensity
K = extinction coefficient
L = path length
0 = opacity

Assuming that shortening the path length affects only the extinction coefficient, Equation 5.5 is the manipulation of Equation 5.4 to show the impact of an altered path length on the measured opacity.

$$0_2 = 1 - \mathrm{EXP}\left[\frac{L_2}{L_1} \ln\left(\frac{1}{1-0_1}\right)\right] \qquad (5.5)$$

where 0_2 = opacity at L_2
0_1 = opactiy at L_1

Since the Hagerstown boiler plant has a significant amount of carbon carry over when coal is fired, most of the reduction in the plume opacity can be attributed to improved combustion conditions within the boiler when the blends were fired.

Particlate Concentration

Figure 53 shows the particulate emission rate as a function of load and blend. Except for the 0:1 (100 percent dRDF) firing, the particulate mass flux in the flue gas was reduced with increasing dRDF substitutions, i.e., from the 1:1 to the 1:2 blend firing. However, the reductions are not significant at the 90 percent confidence level. While the 0:1 firing produced results that differed from the data presented within the 90 percent confidence level, the limitation of only two data points for the 0:1 firing precludes definitive conclusions.

The data show that when 100 percent dRDF was fired, the increase in the fuel ash more than offset the reduction in the fly ash carbon. This improved burnout is confirmed by the filters shown in Figure 54. These filters, which were removed from the EPA Method 5 train, show a color shift from the 1:0 to the 0:1 blend firing. The analysis of carbon in the fly ash, as shown in Figure 42, also indicates a reduction in carbon content with increased boiler load and dRDF substitution for coal.

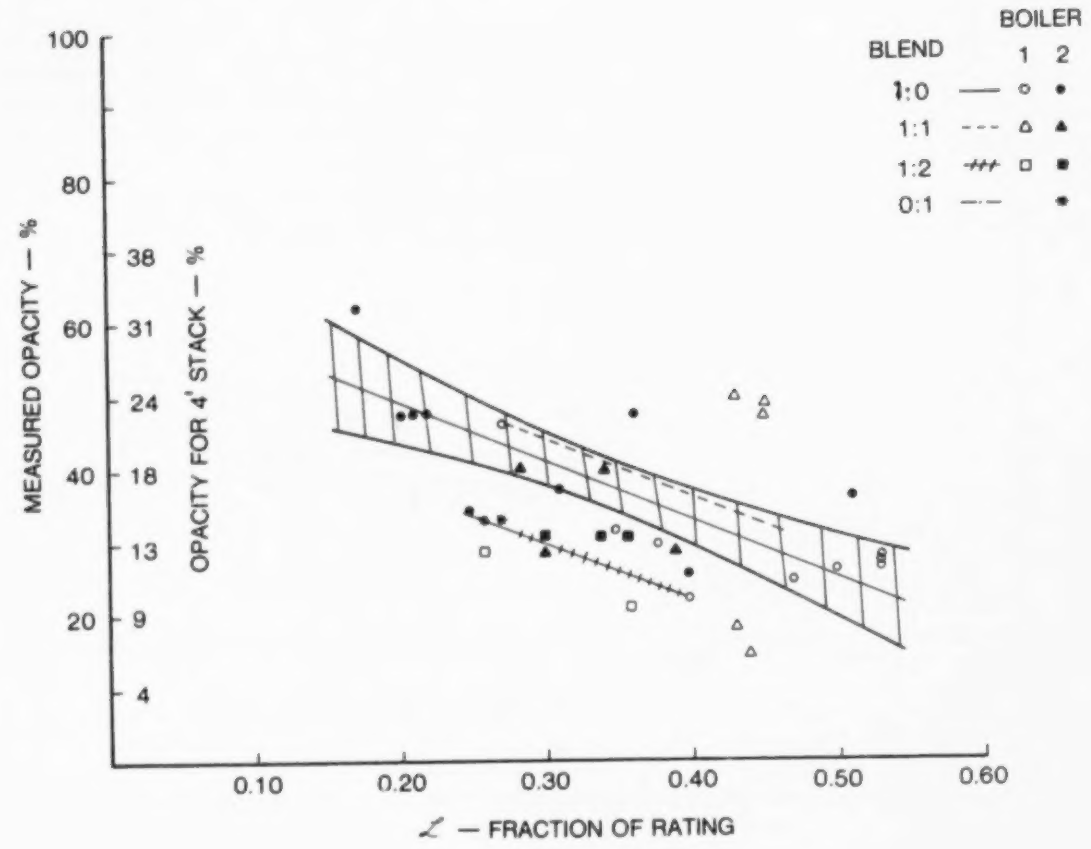


Figure 52. Effects of blend and load on stack opacity.

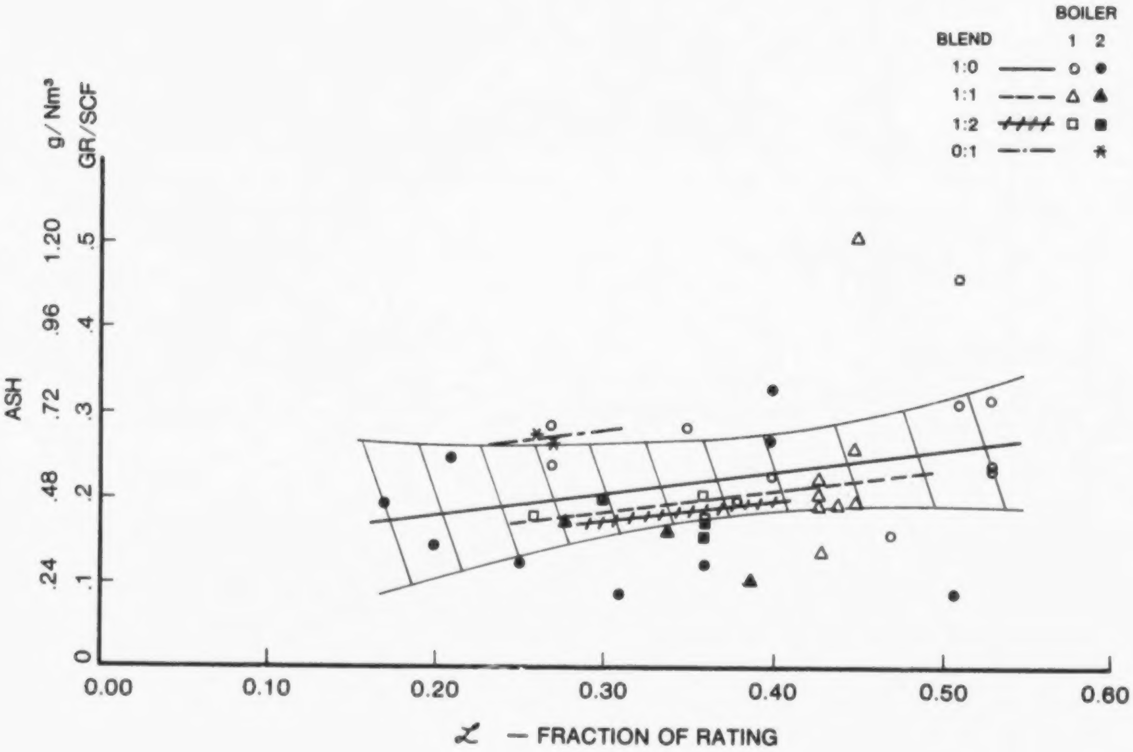


Figure 53. Effects of blend and load on particulate mass emission rate.

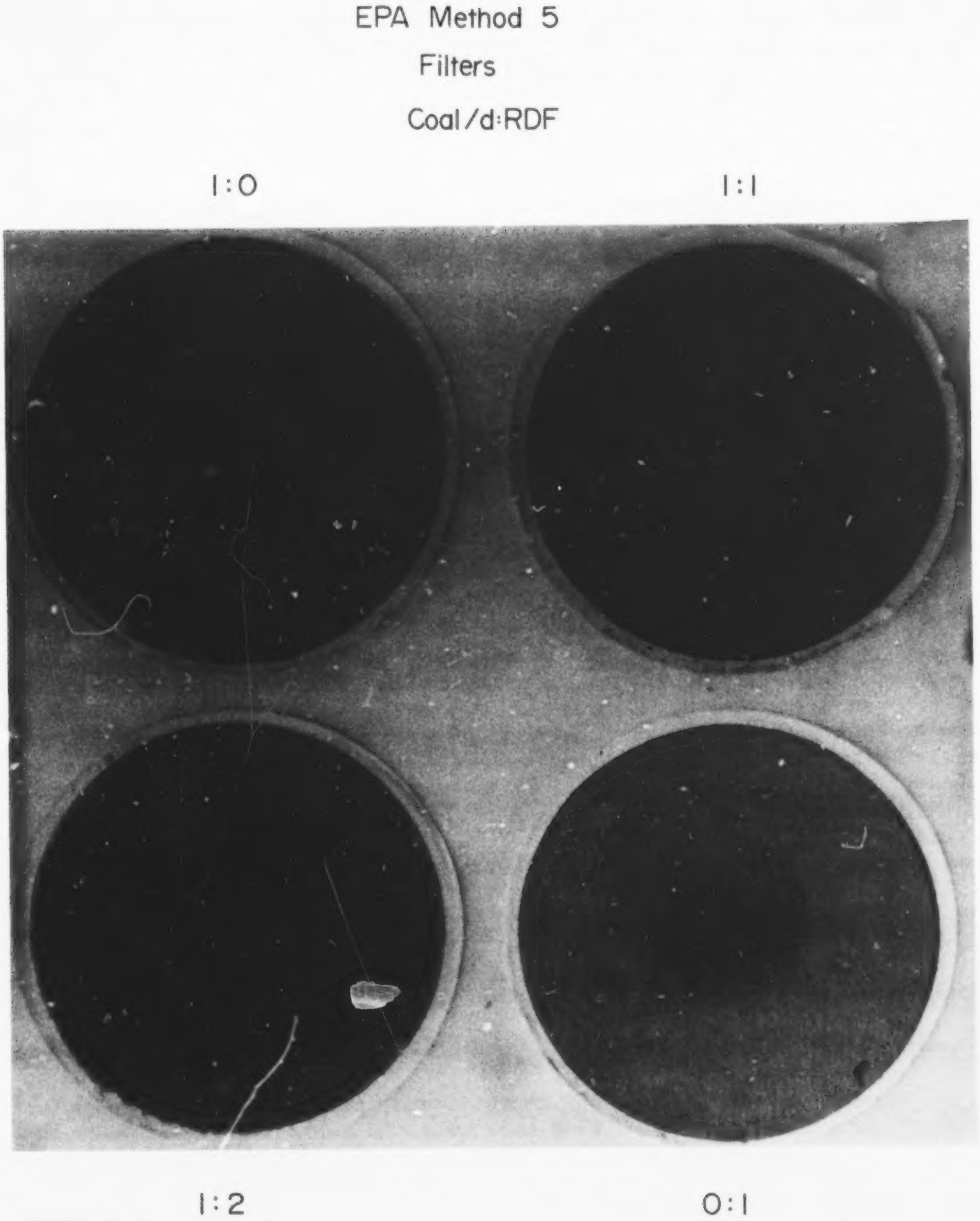

EPA Method 5
Filters
Coal/d:RDF
1:0
1:1
1:2
0:1

Figure 54. Effect of blend on color of stack aerosol.

Size Distribution

Typical of all data results, Figure 55, a size distribution plotted on Rosin-Rammler paper, shows that the cumulative mass vs size distribution plots as a straight line. The two probability plots of the MRI cascade impactor data in Figures 56 and 57 are the averages of all related values for the March and May tests, respectively. Appendix D lists the data for each of the MRI cascade impactor runs.

These plots indicate that as dRDF is substituted for coal, the aerosol size distribution shifts to the fines. This was expected for two reasons: First, improved burnout of the aerosol produces smaller particulates for the same amount of ash. Second, the large number of fine paper platelets in the dRDF causes the number of particles formed from burning a unit of fuel to increase.

Fly Ash Resistivity

The resistivity of the fly ash leaving a source is of interest because the performance of a precipitator is governed by the total particulate concentration, the aerodynamic characteristics of the particles, and the resistivit During design and operation the resistivity determines the power which can be applied to collect the aerosol as well as the extent to which the aerosol can be re-entrained into the flue gas stream after "collection."

The coal-only firing produced a resistivity generally less than 10^6 ohm- This unusually low resisitivity is a direct result of the high carbon content in the fly ash. At this level of resistivity, particles collect at the wall of the precipitator, rapidly lose their charge, and re-enter the gas stream. Consequently, an ESP does not perform well when the particle cloud has a low resistivity. Figure 58 presents the resistivity results for coal-only and blend firing. The 1:1 blend fly ash had resistivities about 10^{10} ohm-cm. This resistivity is within the range of 10^8 to 10^{10} ohm-cm required for efficient precipitator performance. The fly ash from the 1:2 and 0:1 blends may have resistivities which are too high (10^{12} ohm-cm) for good ESP collection efficiencies. Table 13 illustrates the resistivities of the various blends for the March and May tests.

The resistivity was not plotted against carbon content or gas temperatu since the data were too limited to make the results meaningful.

Overall ESP Performance

To test the aerosol control capability at the Hagerstown boiler plant while firing coal and coal:dRDF blends, a field-portable, 5-cell ESP was installed and tested between April 28 and May 17. This was the only period when the precipitator could be used at the Hagerstown plant because of other test demands. The precipitator is owned by the EPA Industrial Environmental Research Laboratory in Research Triangle Park, North Carolina, and operated by Monsanto Research Corporation. The precipitator system was housed in two trailers, one for the five precipitator cells with independent power supplie and the other for the precipitator electrical monitors and an aerosol

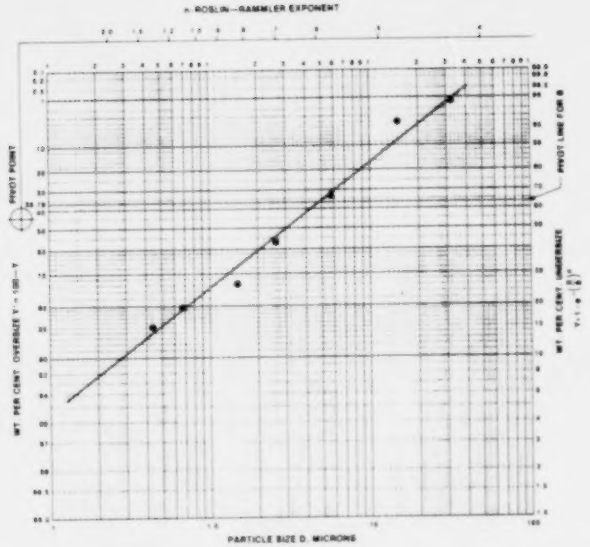


Figure 55. Typical MRI cascade impactor results for blend firing.

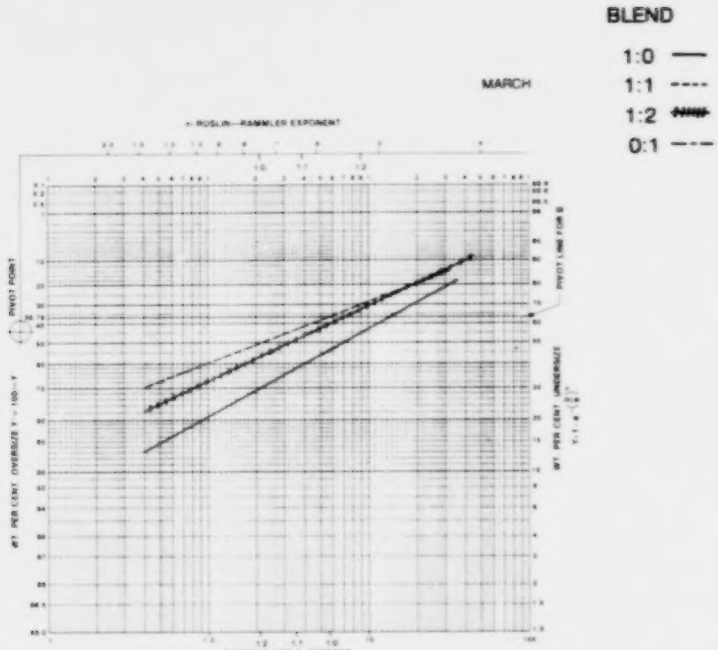


Figure 56. Average size distribution for coal, blend, and dRDF firings during March tests.

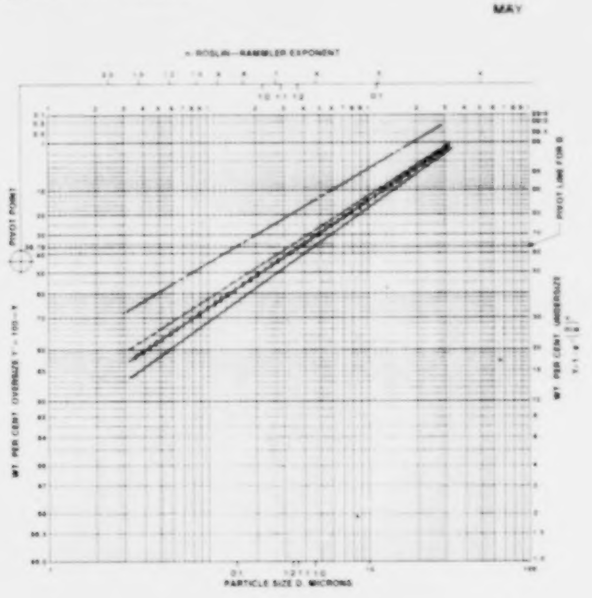


Figure 57. Average size distribution for coal, blend, and dRDF firings during May tests.

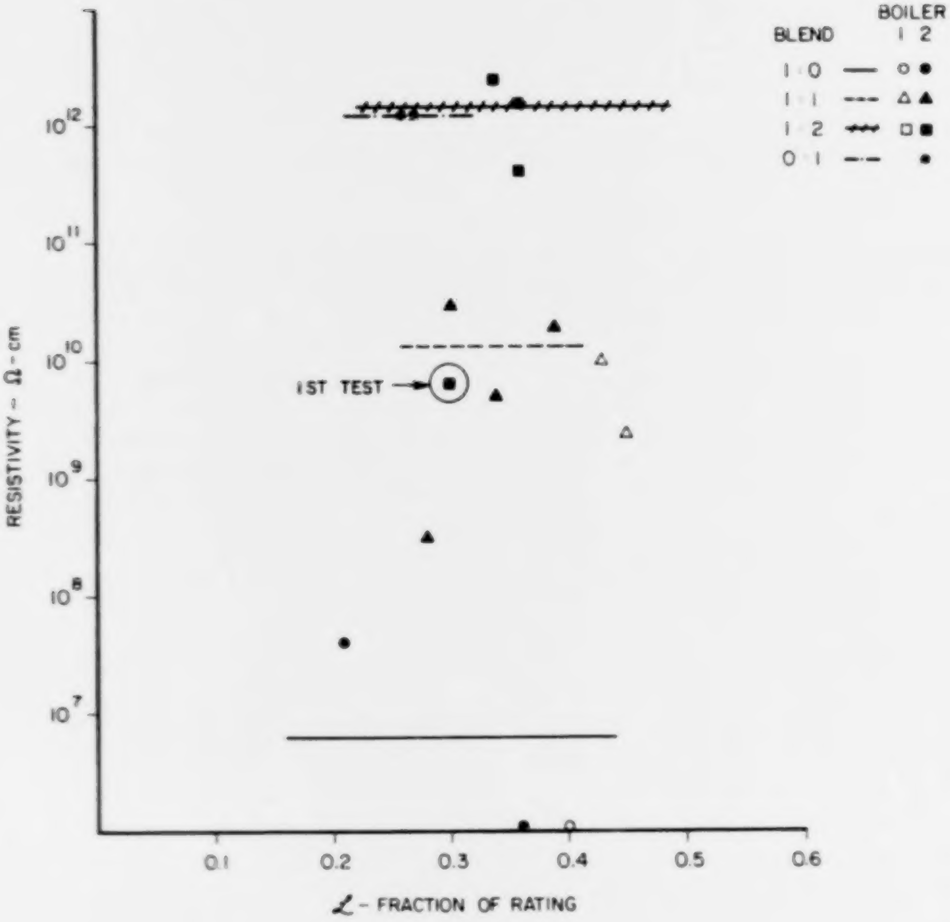


Figure 58. Effects of blend and load on aerosol resistivity.

TABLE 13. EFFECT OF BLEND ON AEROSOL RESISTIVITY

	Resistivity (Ω-cm)	
Blend	March Tests	May Tests
1:0	$<10^7$	6×10^7
1:1	8×10^9	2×10^{10}
1:2	--	1×10^{12}
0:1	--	1×10^{12}

laboratory. As shown in Figure 59, the precipitator cells are of the plate and frame construction with the charging electrodes installed in a pipe frame support centered between parallel, smooth-surface collecting electrodes.

Since the charging electrodes are suspended from dielectric blocks resting across the tops of the grounded electrodes, an aerosol accumulating on the dielectric block tends to short circuit the cells. Because of such short circuits during the testing, the number of operating cells progressively decreased. Consequently, the results from this test cannot be considered representative of the data which might be collected from a commercially available ESP. Additional ESP testing is planned for the demonstration test. Appendix E includes the data acquired by Monsanto during the May testing and a discussion of the results.

GASEOUS EMISSIONS TEST RESULTS

The following sections detail the test results for the following gaseous emissions: SO_2, oxides of nitrogen, halogens, and hydrocarbons.

SO_2

The sulfur oxide level in the flue gas is of particular interest to precipitator designers since it is related to aerosol resistivity. Figure 60 shows the blend effect on the overall sulfur dioxide emission rate as a function of boiler load. The reduction in overall SO_2 emissions with the replacement of higher sulfur coal by 0.6 percent sulfur dRDF is significant for the 1:2 and 0:1 blend firings. While the 1:1 blend firings showed a reduction in SO_2 when compared to coal, the difference did not exceed the 90 percent confidence limits. Very good agreement was obtained between the sulfur oxide emissions as determined by the continuous monitoring electro chemical sensor and the wet chemistry determinations. Reference is made to Tables A-2 and A-3 in Appendix A. The SO_x for test days May 10 through May 13 were: blend 1:1

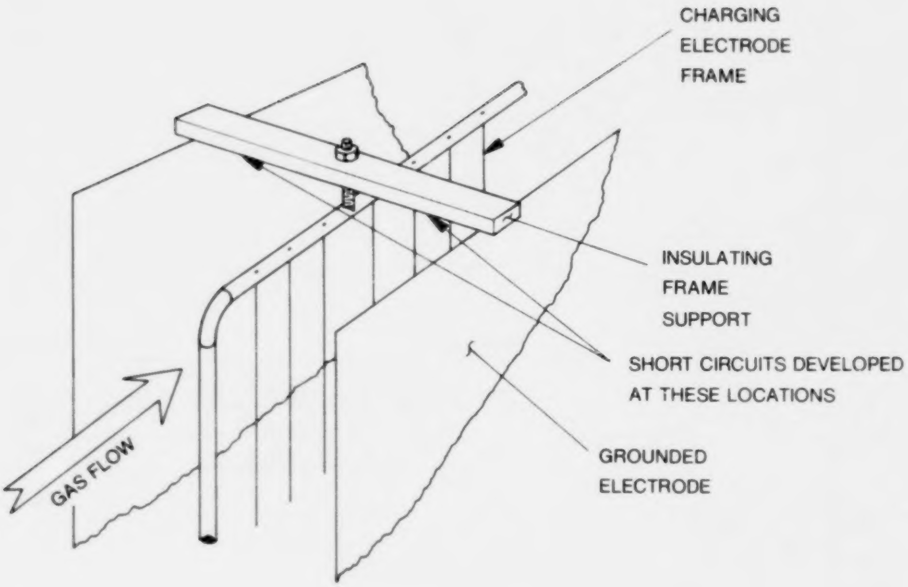
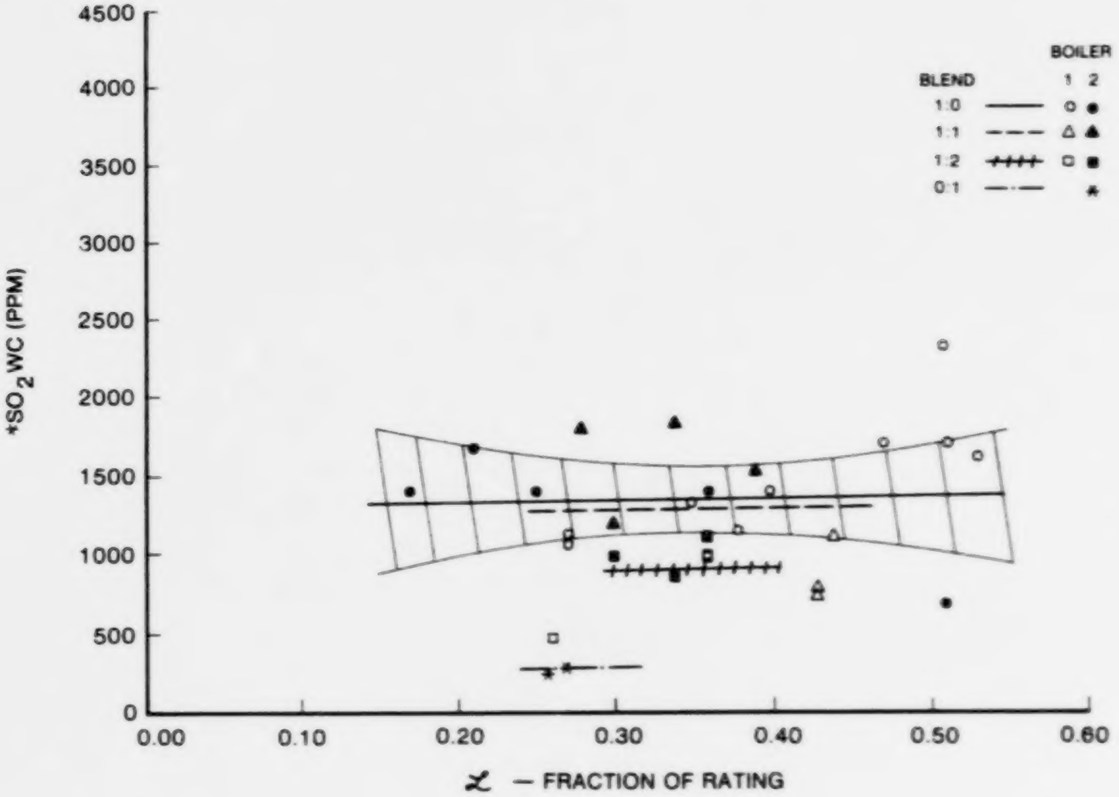

CHARGING
ELECTRODE
FRAME
INSULATING
FRAME
SUPPORT
SHORT CIRCUITS DEVELOPED
AT THESE LOCATIONS
GROUNDED
ELECTRODE
GAS FLOW

Figure 59. Cell configuration in the portable ESP.



* SO_2 WC is SO_2 as determined by wet chemistry.

Figure 60. Effects of blend and load on sulfur dioxide emissions.

1334 ppm (meter), 1309 ppm (wet chemistry), and blend 1:2 825 ppm (meter), 825 ppm (wet chemistry). As would be expected, the reduction in sulfur emission was proportional to the reduction of the sulfur in the fuel combusted. Reference is made to Table 5 and Tables A-1 through A-4 in Appendix A for verification of the reduction in sulfur emissions as a function of the sulfur in the fuel combusted.

Oxides of Nitrogen

The results from the on-line NO_x analyzer determinations are shown in Figure 61 and Table 14. The plot of NO_x versus load as a function of blend has considerable scatter. The random pattern of the line placement for blend firing suggests that there is no apparent relationship between the blend firings and the NO_x emissions.

Figure 62 shows the NO_x emissions replotted as a function of excess air. All the results are similar in that they fall within the 90 percent confidence level. Table 14 summarizes all the NO_x concentrations as determined by both wet chemistry and the Theta Sensor trigas analyzer.

Halogens

Of concern to many people is the emission of chlorine from the combustion of dRDF. Although chlorine levels (weight basis) in dRDF are about the same as those found in some coals burned throughout the United States and Europe, the coal:dRDF blends emit more chlorine per megajoule than most coals because of their lower heat content. The chlorine level per magajoule equivalent for the coal:dRDF firing (1:2 blend) was seven times greater than the level for coal-only firing.

Figures 63 and 64 show the emission rates for chlorine and fluorine, respectively, as a function of coal:dRDF blend and boiler loads. Since the chlorine emission regression lines for blend firing are well outside those for coal-only firing, the blend firing apparently had substantially greater chlorine emission rates. Since fluorine concentrations were omitted in the laboratory analysis of the base fuel, the significance of the fluorine emissions for blend versus coal-only firing cannot be established.

Hydrocarbons

Hydrocarbon emissions are particularly important because of their smog forming potential. Figure 65 shows the hydrocarbon emissions as a function of boiler load and coal:dRDF blend. The hydrocarbon emissions from the blend firing was not significantly different from the coal firing. The single data point at 100 percent dRDF firing (55 ppm) suggests that further testing may be required at higher dRDF substitution ratios to verify this increase.

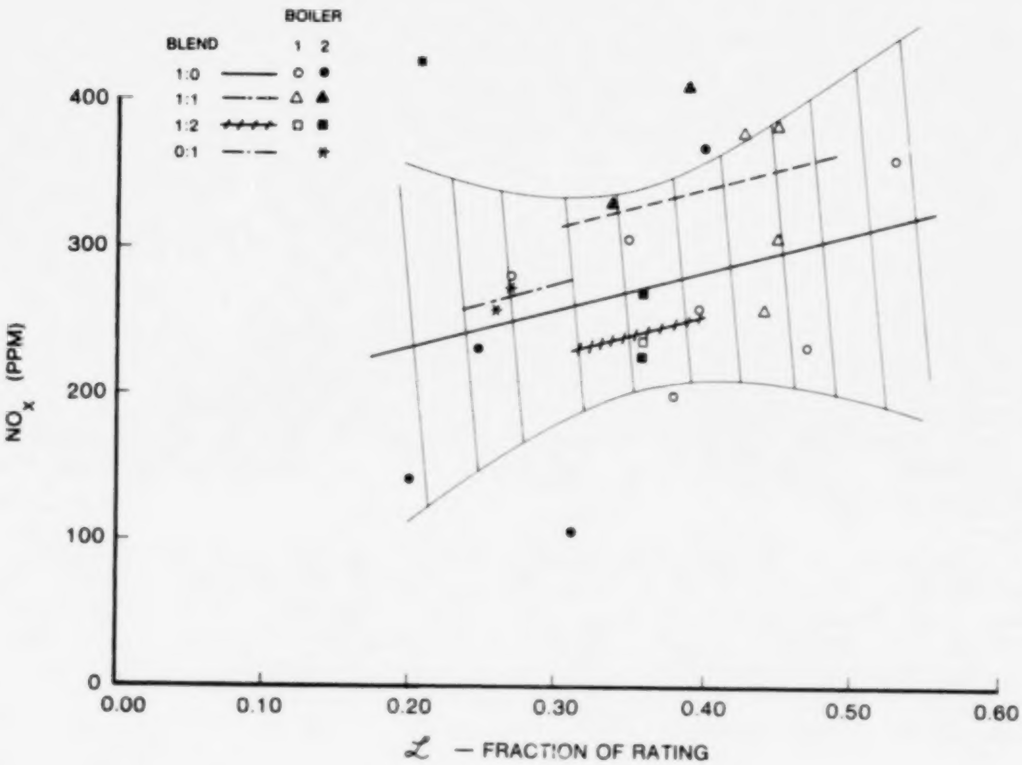


Figure 61. Effects of blend and load on nitrogen oxide emissions.

TABLE 14. RELATIONSHIP OF NO_x CONCENTRATION AND EXCESS AIR PERCENTAGE FOR COAL, BLEND, AND dRDF FIRINGS

Date	NO_x M(ppm)	NO_x WC(ppm)	Percent Excess Air
1:0 Blend (coal only)			
3/21	362		104
3/22	257		72
3/28	197		92
3/31	277		71
4/1	300		82
5/3	230	318	72
5/4	141		116
5/5	105	238	84
5/16	424	449	147
1/20	358		108
1/20	358		88
1/21	228		86
1/24		424	87
1/25		594	110
1:1 Blend Firing			
3/24	255		102
5/12	326	360	109
5/13	405	386	101
1:2 Blend			
3/29	232		94
5/10	223	192	138
5/11	305	273	132
0:1 Blend			
5/14	272	274	133
5/14	255	247	106

Notes: 1. NO_xM is - NO_x as determined by the Theta Sensors, Inc. Tri-gas Meter.

2. NO_xWC is - NO_x as determined by the EPA Method 7 Wet Chemistry.

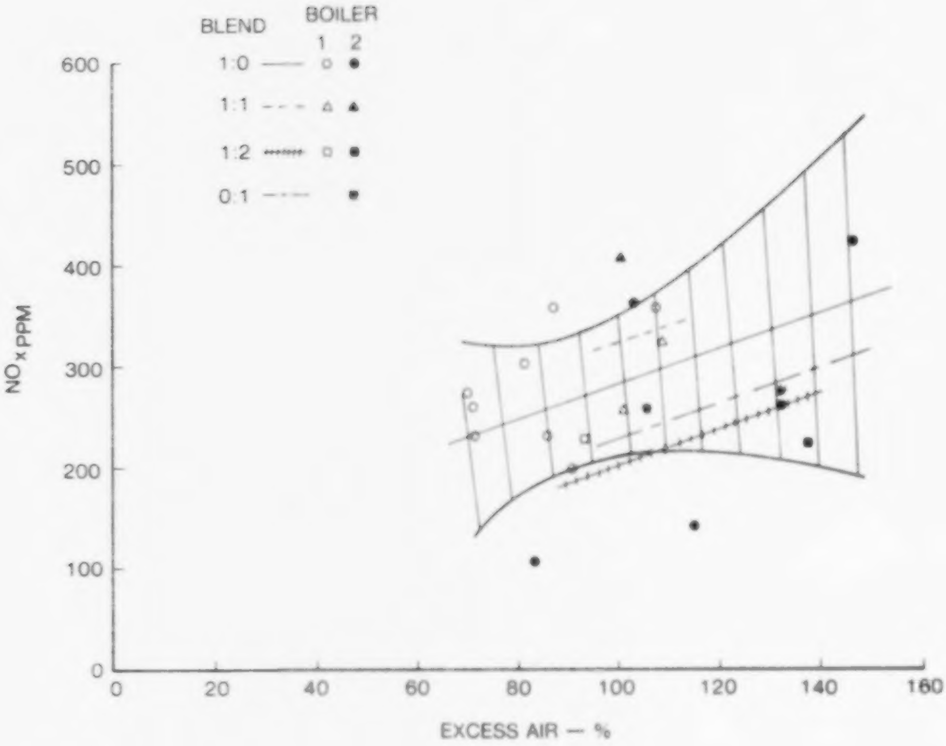


Figure 62. Effects of blend and excess air on nitrogen oxide emissions.

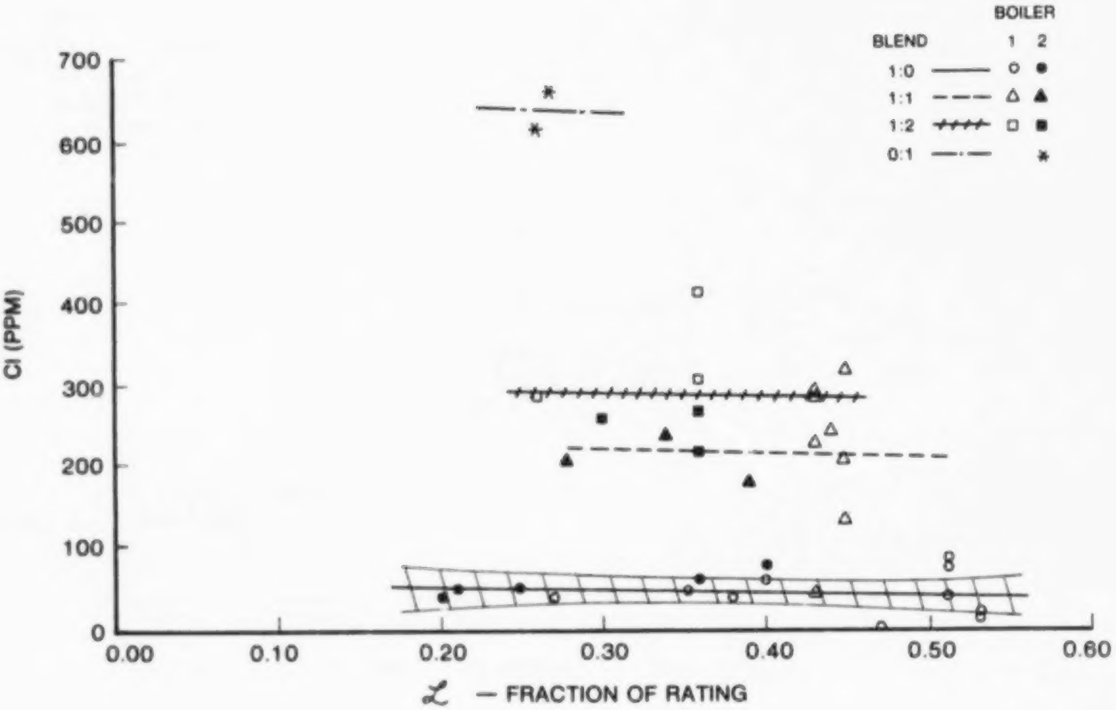


Figure 63. Effects of blend and load on chlorine emissions.

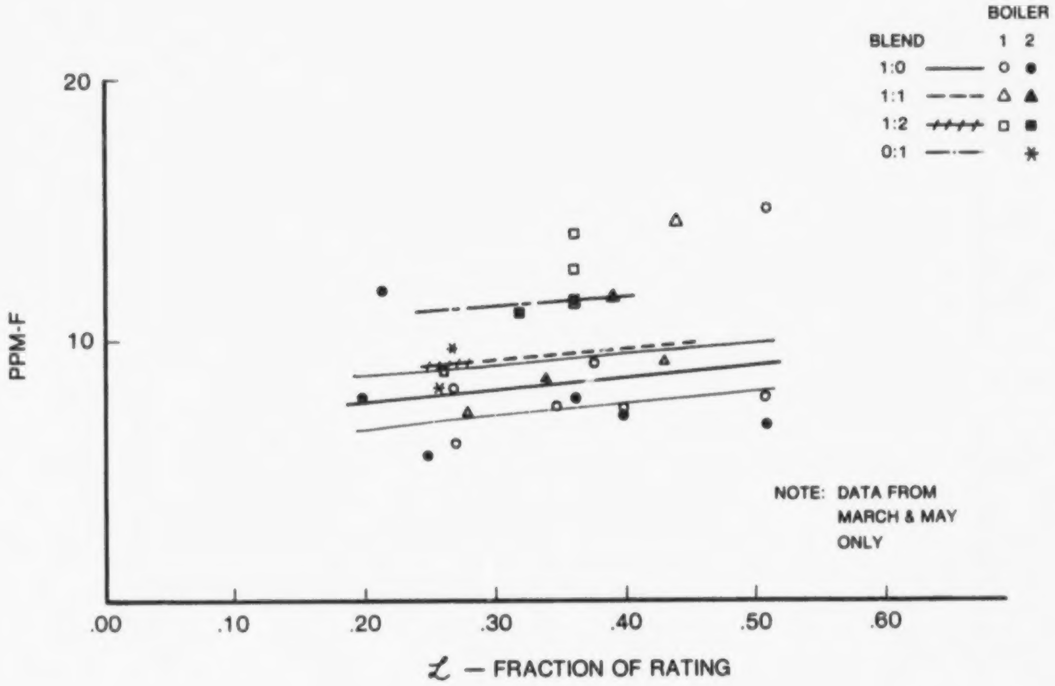


Figure 64. Effects of blend and load on fluorine emissions.

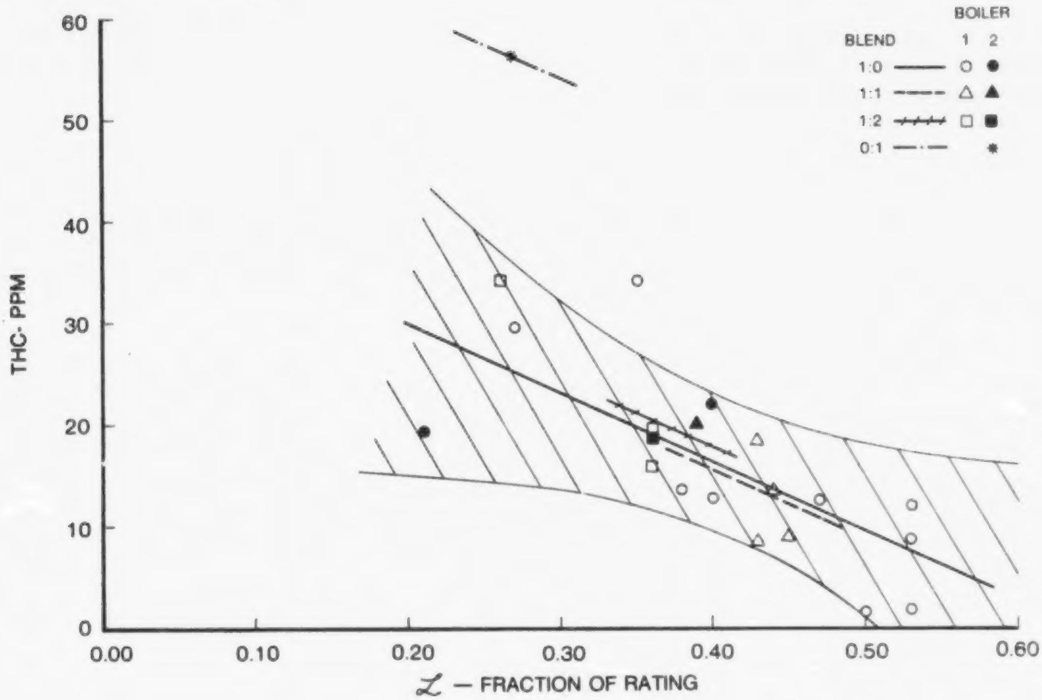


Figure 65. Effects of blend and load on hydrocarbon emissions.

TRACE COMPOUND EMISSIONS TEST RESULTS

While not yet regulated, the emissions of potentially carcinogenic polycyclic hydrocarbons and hazardous heavy metals from stationary combustion sources are coming under intense scrutiny. Therefore, the flue gases were evaluated for polycyclic organic compounds and heavy metal emissions.

Trace Organic Emissions

Table 15 lists the results of the GC-Mass Spectrometer Analysis of the Battelle Tenex samples. The overall emissions of polycyclic organic materials (POM's) for the coal-only and the blend firings were very low. Morever, all the monitored emissions were below the threshold limits proposed by the National Academy of Science. Since the increase in emissions for the 1:1 blend firing is based on the data of a sample taken during boiler switchover, this increase is questionable.

TABLE 15. POM CONCENTRATIONS FOR COAL AND BLEND FIRINGS

COMPONENT	1:1 ppb	1:2 ppb	COAL 1:0 ppb	1:1 Ng/m^3	1:2 Ng/m^3	COAL 1:0 Ng/m^3
Anthracene/Phenanthrene	0.0736	0.0516	0.00086	543	380	6
Methyl anthracenes	0.0126	0.0052	0.00032	100	42	3
Fluoranthene	0.0164	0.0064	0.00030	137	54	3
Pyrene	0.0039	0.0027	0.0018	33	23	15
Methyl Pyrene/ Fluoranthene	0.00043	<0.0002	<0.0002	4	<1.0	<1.0
Benzo(c)phenanthrene	<0.0002	n/d	n/d	<1.0	n/d	n/d
Chrysene/Benz(a) anthracene	n/d	n/d	n/d	n/d	n/d	n/d
Methyl chrysenes	n/d	n/d	n/d	n/d	n/d	n/d
7,12-Dimethylbenz(a) anthracene	n/d	n/d	n/d	n/d	n/d	n/d
Benzo fluoranthenes	n/d	n/d	n/d	n/d	n/d	n/d
Benz (a) pyrene	n/d	n/d	n/d	n/d	n/d	n/d
Benz (e) pyrene	n/d	n/d	n/d	n/d	n/d	n/d
Perylene	n/d	n/d	n/d	n/d	n/d	n/d
Methyl Benzopyrene	n/d	n/d	n/d	n/d	n/d	n/d
3-Methyl Chloranthrene	n/d	n/d	n/d	n/d	n/d	n/d
Indeno(1,2,3,-cd) pyrene	n/d	n/d	n/d	n/d	n/d	n/d
Benzo(ghi)perylene	n/d	n/d	n/d	n/d	n/d	n/d
Dibenzo(a,h) anthracene	n/d	n/d	n/d	n/d	n/d	n/d
Dibenzo (c, x) carbazole	n/d	n/d	n/d	n/d	n/d	n/d
Dibenz (ai and ah) pyrenes	n/d	n/d	n/d	n/d	n/d	n/d
Coronene	n/d	n/d	n/d	n/d	n/d	n/d

Trace Inorganic Emissions

Table 16 lists the concentrations of the fuel ash trace metals found in two coal and two dRDF samples. The concentrations were determined by first preparing the specimens by oxygen plasma ashing and then analyzing them with spark source mass spectrometry. The enrichment ratios indicate the greater amount of metals in dRDF than in coal. The range of reported fuel metal values clearly indicates the heterogeneous content of the dRDF and the variability of the metalic material in coal.

The detailed heavy metal ash analyses are presented in Appendix F and summarized in Table 17. This table lists the average emission rates for each test battery. The March and May data were separated to eliminate the effects of normalizing the data to the reference coal. Table 18 is a manipulation of the data in Table 17 to present the emission rate data in terms of enrichment functions. For example, Table 18 shows that 43.3 times more lead was emitted in the total particulates when firing dRDF only than when firing coal only. In addition, while some metals were enriched, others had reduced emission rates.

Tables 17 and 18 also show the enrichment of certain metals in the bottom ash, the reinjected fly ash, and the collected fly ash. The presence of these metals in the ash implies an increased possibility of heavy metal leaching when boiler ash is landfilled or used for various applications. The significance of this leaching is unknown.

The amounts of the various metals found for all blends were generally normal except for the amount of arsenic which was fairly high. Most notable of the trends was the variation of several metals with the coal:dRDF ratios: whereas the concentrations of Br, Mn, Pb, and Sb generally increased with increasing dRDF substitution in the coal:dRDF blends, the concentrations of As, Ni, and Vn decreased. Although these trends are not definitive, they are probably true since they were also observed in the data for the fly ash leachates.

While variations of the heavy metal concentrations with particle size were poorly defined, the concentrations of As, Ga, Na, and probably Sb generally increased with decreasing particle size. In contrast, the concentrations of Br and Mn markedly increased with increasing particle size. Appendix F provides a detailed summary of the heavy metal data.

On the basis of previous work with coal aerosols and incinerator fly ash,[6] it would be expected that such metals as Br, Mn, Pb, and Sb would have higher concentrations in RDF than in coal and that As, Ni, and V would have a greater affinity to coal than to RDF. Similarly, the affinity of As, Ga, Na, and Sb to small particles would be expected since these metals can be volatilized during combustion and then adsorbed onto the more developed surface

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[6] Kaakinen, J. W., et al. Trace Element Behavior in Coal Fired Power Plants. Environmental Science and Technology, Volume 9. pp. 862-869.

TABLE 16. TRACE METAL CONCENTRATIONS FOUND IN COAL AND dRDF FUEL

	Coal Sample		d-RDF Sample		dRDF:COAL Enrichment Ratio	
	#1	#2	#1	#2		
Element	ppm	ppm	ppm	ppm	Per kg Ash	Per MJ
Li	50	54	10	<0.1	0.097	.3
Be	1	4	0.05	<0.1	0.03	.1
B	30	23	20	<0.1	0.38	1.1
F	<5	≈150	10	≈36	0.30	.9
Na	≈1000	MC	High	MC		
Mg	1000	MC	High	MC		
Al	High	MC	High	MC		
Si	High	MC	High	MC		
P	300	MC	High	MC		
S	≈1%	MC	2000	MC		
Cl	100	MC	2000	MC		
K	High	MC	High	MC		
Ca	High	MC	High	MC		
Sc	10	14	<1	0.7	0.12	.4
Ti	2000	MC	2000	MC		
V	40	97	10	8	0.13	.4
Cr	100	88	40	260	1.60	4.6
Mn	100	22	500	>470	7.95	22.9
Fe	High	MC	High	MC		
Co	20	7	1	2	0.11	.3
Ni	100	19	20	15	0.29	.8
Cu	10	13	30	41	3.09	8.9
Zn	5	16	500	300	38.10	109.9
Ga	20	32	2	4	0.12	.3
Ge	<1	≤5	<0.3	0.1	0.07	.2
As	10	13	4	4	0.35	1
Se	<1	12	<0.5	0.4	0.07	.2
Br	3	19	10	4	0.64	1.8
Rb	100	33	20	3	0.17	.5
Sr	300	690	150	74	0.23	.7
Y	10	70	2	1	0.04	.1
Zr	100	280	50	13	0.17	.5
Nb	5	11	1	2	0.19	.5
Mo	10	11	10	4	0.67	1.9
Ru	<1	0	<0.2	0	0.20	.6
Rh	<0.3	0	<0.1	0	3.00	8.7
Pd	<1	0	<0.2	0	0.20	.6
Ag	<0.6	1	1	0.4	0.88	2.5

(continued)

TABLE 16. (continued)

Element	Coal Sample #1 ppm	 #2 ppm	d-RFD Sample #1 ppm	 #2 ppm	dRDF:COAL Enrichment Ratio Per kg Ash	 Per MJ
Cd	<1	2	≤0.6	0.3	0.3	.9
In	<1	STD	<0.06	STD		
Sn	<1	2	20	8	9.33	26.9
Sb	<2	<0.8	1	9	3.57	10.1
Te	<1	<0.8	<0.2	0	0.11	.3
I	1	5	0.6	0.1	0.12	.3
Cs	≤3	3	0.2	0.2	0.07	.2
Ba	100	410	200	330	1.04	3
La	10	44	2	3	0.09	.3
Ce	20	110	10	3	0.1	.3
Pr	1	5	0.5	0.5	0.17	.5
Nd	4	11	15	[illegible]	1.03	3
Sm	<1	7	<0.3	0.4	0.09	.3
Eu	<0.6	1	<0.2	0.1	0.19	.5
Gd	<1	2	<0.3	0.1	0.13	.4
Tb	<0.4	0.9	<0.1	0.1	0.15	.4
Dy	<1	0	<0.3	0.2	0.5	1.4
Ho	<0.4	0	<0.1	0.1	0.5	1.4
Er	<1	0	<0.3	0.1	0.4	1.2
Tm	<4	0	<0.1	0	0.03	.07
Yb	<1	0	<0.3	0	0.3	.9
Lu	<0.4	0	<0.1	0	0.25	.7
Hf	<2	9	<0.3	0	0.03	.08
Ta	<2	0	<0.1	0	0.05	.1
W	<2	5	<0.3	0	0.04	.1
Re	<1	0	<0.3	0	0.3	.9
Os	<1	0	<0.3	0	0.3	.9
Ir	<1	0	<0.3	0	0.3	.9
Pt	<2	0	<0.3	0	0.15	.4
Au	<2	0	<0.3	0	0.15	.4
Hg	<5	<0.8	<0.3	<0.1	0.07	.2
Tl	<1	0	<0.1	0	0.1	.3
Pb	≤2	8	500	170	67	193
Bi	<1	0	0.2	0.1	0.3	.9
Th	<1	17	<0.1	0.7	0.04	.1
U	<1	8	<0.1	0.5	0.07	.2

TABLE 17. AVERAGE HEAVY METAL EMISSIONS IN ASH FROM BLEND FIRING TESTS

	BLEND	No. of Samples Analyzed	Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
							MARCH								
Threshold Limit Level µg/m^3	---		200	20	500	100	100	1000	---	5000	---	---	500	10	
Total Particulate stack - µg/m^3	1:0	7	228	≤4.43	173	≤7.85	35.1	32.6	47.7	592	≤51.7	≤1.46	<87.2	<8.72	<87.2
	1:1	3	3975	79.4	45.9	19.6	33.5	32.1	64.6	6012	96.1	3.36	<52.2	12.0	<52.2
	1:2	3	7660	233	44.9	12.3	47.6	41.0	101	8569	82.5	4.99	≤87.3	17.1	59.6
Bottom Ash - µg/kg	1:0	1	<12.5	<.75	11.0	<0.4	22.5	20.0	51.0	31.2	15.0	0.50	<25	<2.5	<25
	1:1	1	26.3	<.8	39.3	<0.4	25.6	27.4	138	73.3	152	3.58	<25	<2.5	<25
	1:2	1	128	0.75	36.7	<0.4	42.5	139	250	188	200	5.00	<25	<2.5	<25
Multiclone Reinjection Fly Ash - µg/kg	1:0	1	16.3	<.75	34.4	<0.4	8.75	15.0	105	31.2	<12.5	1.88	<25	<2.5	<25
	1:1	2	97.5	1.12	39.3	<.68	12.6	16.9	193	134	15	2.50	<25	<2.5	≤25
	1:2	1	109	1.5	66	<0.4	15.0	18.7	300	194	17.5	2.25	<25	<2.5	25

	BLEND	No. of Samples Analyzed	Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
							MAY								
Threshold Limit Level µg/m^3	---		200	20	500	100	100	1000	---	5000	---	---	500	10 5.75+120.	
Total Particulate stack - µg/m^3	1:0	7	230	4.33	184	≤5.57	50.7	49.5	30.4	596	50.1	≤1.45	<65.6	<6.56	<65.6
	1:1	3	4237	72.4	153	15.7	35.4	35.9	62.6	5063	82.4	2.70	<48.5	<6.51	<48.5
	1:2	3	8217	220	126	11.4	55.4	50.9	115	8317	134	3.47	59.1	19.4	<59.1
	0:1	2	9953	267	49.4	94.7	79.7	29.4	275	8033	203	6.07	<107	29.7	<107
Bottom Ash - µg/kg	1:0	2	<12.5	<.75	16.1	<0.4	8.75	20.0	40.5	68.8	≤18.8	0.50	<25	62.9	<25
	1:1	2	46.3	≤.75	35.0	<0.4	23.7	33.2	170	112.5	221	3.31	<25	<2.5	<25
	1:2	2	65.0	.75	28.8	<0.4	20.7	22.1	135	73.4	≥136	3.62	<25	<2.5	<25
	0:1	1	169	2.13	56.3	<0.4	50.0	35.0	43.5	539	205	3.6	<25	88.8	<25
Multiclone Reinjection Fly Ash - µg/kg	1:0	1	20.0	<.75	48.1	<0.4	21.3	26.2	45.0	50.0	15.0	1.0	<25	<2.5	25
	1:1	1	92.5	1.00	49.5	0.58	21.3	23.7	120	156	22.5	3.0	<25	<2.5	25
	1:2	2	165	1.9	34.9	≤.415	23.6	23.2	132	292	42.2	3.0	<26	<2.5	≤26
	0:1	2	363	7.88	46.3	≤.440	69.4	40.9	81.3	1118	88.4	4.84	<25	6.0	≤25
Collector Ash µg/kg	1:0	3	20.8	<0.75	76.3	<0.4	17.7	87.5	49.7	60.4	15.0	2.09	<25	<2.5	25
	1:1	4	217	3.58	80.4	≤.545	19.7	25.2	145	343	27.8	3.58	<25	<2.5	≤28.7
	1:2	3	274	6.00	43.5	≤1.0	34.9	31.9	328	608	39.9	1.63	<25	<2.5	27.3
	0:1	2	1012	25.4	103.5	≤0.65	185	75.4	123	---	149	8.08	<26.3	13.7	41.6

TABLE 18. BLEND HEAVY METAL TO COAL-ONLY HEAVY METAL RATIOS IN ASH SAMPLES

MARCH

	BLEND	Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
Total Particulates stack - µg/m^3	1:0	1.0	1.0*	1.0	1.0*	1.0	1.0	1.0	1.0	1.0*	1.0*	<	1.0*	<
	1:1	17.4	17.9	.265	2.50	4.27	.985	1.35	10.2	1.86	2.30		1.38	
	1:2	33.6	52.6	.259	1.57	6.06	1.26	2.12	14.5	1.60	3.42		1.96	
Bottom Ash - µg/kg	1:0	1.0*	<	1.0	<	1.0	1.0	1.0	1.0	1.0	1.0	<	<	<
	1:1	2.10		3.57		1.14	1.37	2.71	2.35	10.1	7.16			
	1:2	10.2		3.34		1.89	6.95	4.90	6.03	13.3	10.0			
Multiclone Reinjection Fly Ash µg/kg	1:0	1.0	1.0*	1.0	<	1.0	1.0	1.0	1.0	1.0*	1.0	<	<	1.0*
	1:1	5.98	1.49	1.14		1.44	1.13	1.84	4.29	1.2	1.33			1.0*
	1:2	6.69	2.00	1.92		1.71	1.25	2.86	6.22	1.4	1.20			1.0

MAY

	BLEND	Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
Total Particulate stack - µg/m^3	1:0	1.0	1.0	1.0	1.0*	1.0	1.0	1.0	1.0	1.0	1.0*	<	1.0*	<
	1:1	18.4	16.7	.832	2.82	.698	.725	2.06	9.51	1.64	1.86		1.0*	
	1:2	35.7	50.8	.685	2.05	1.09	1.03	3.78	14.0	2.67	2.39		2.96	
	0:1	43.3	61.7	.269	17.0	1.57	.594	9.05	13.5	4.05	4.19		4.53	
Bottom Ash - µg/kg	1:0	1.0*	1.0*	1.0	<	1.0	1.0	1.0	1.0	1.0*	1.0	<	1.0**	<
	1:1	3.70	1.0*	2.17		2.71	1.66	4.20	1.64	11.8	6.62		<.435*	
	1:2	5.20	1.0	1.79		2.37	1.11	3.33	1.07	9.89*	7.24		<.435*	
	0:1	13.5	2.84	3.50		5.71	1.75	1.07	7.83	10.9	7.20		15.4	
Collector Ash - µg/kg	1:0	1.0	1.0*	1.0	<	1.0	1.0	1.0	1.0	1.0	1.0	<	1.0*	1.0
	1:1	10.4	4.77	1.05*		1.11	.288	2.92	5.68	1.85	1.71		1.0*	1.0*
	1:2	13.2	8.0	.570		1.97	.365	6.60	10.1	2.66	0.780		1.0*	1.09
	0:1	48.6	33.9	1.36		10.5	.862	2.47	---	9.93	3.87		5.48	1.66
Multiclone Reinjection Fly ash - µg/kg	1:0	1.0	1.0*	1.0	<	1.0	1.0	1.0	1.0	1.0	1.0	<	1.0*	1.0
	1:1	4.63	1.33	1.03		1.0	.905	2.67	3.12	1.5	3.0		1.0*	1.0
	1:2	8.25	2.53	.726		1.11	.885	2.93	5.84	2.81	3.0		1.0*	<1.0*
	0:1	18.2	10.5	.963		3.26	1.56	1.81	22.4	5.89	4.84		2.4	<1.0*

< Below the detection limit
* Extreme value deleted

area of the small particles. The increasing Br and Mn concentrations with increasing particle size cannot be explained.

The MRI collector stages for coal-only, blend, and dRDF-only firing in May were accumulated and sent to Colorado State University for analysis. Contained in Appendix G, the University's complete report presents considerable information about both the chemical characteristics and the potential environmental impact of dRDF-coal fly ash. The following trends are based on the data of Table G-3 in Appendix G.

First, the amounts of most metals that are soluble increase with increasing dRDF fraction of the original fuel. While this trend is apparent for Ca, Cu, K, Mg, Mo, Na, Si, Cl^-, NO^-_3, and SO_4^{2-}, it may also exist for B, Ba, Cd, and F^-. Ni and P, and possibly Cr and Sr, have a reverse trend. Since many of the major matrix metals have increasing solubility with increasing dRDF percentage, the addition of dRDF to coal might result in greater bulk solubility (as well as greater trace metal mobilization) than that evidenced in the fly ash of pure coal. This increased solubility may require special procedures for landfill disposal.

Second, the metal mobilization increased with decreasing particle size. While this trend is apparent for Cd, Cr, Cu, K, Mn, Mo, Na, Ni, Pb, and Cl^-, it may also exist for Ba, Be, P, and F^-. This trend may be due to the condensation of these metals from vapor onto the particulate surfaces or to the more efficient formation of soluble oxides (i.e., calcining) in small particles. With the first supposition, similar size dependencies would be expected for both the bulk and the soluble metal concentrations. However, such dependencies would not be expected if solubility is the direct result of chemical reaction at a particle surface. In any event, the available data are not sufficient to rule out either supposition.

In the analysis of the fractional solubility of coal-dRDF fly ash, Al, Ba, Mg, P, Si, and Sr have a very low solubility (<10 percent); Be, Cd, K, Mn, and Na have a moderate solubility (≈20-80 percent); and Ca has a very high solubility.

Several metals, particularly Mn, have an increasing fractional solubility with decreasing particle size. Since Mn exhibits no dependence of concentration on particle size, its solubility increase with decreasing particle size is due to its more efficient calcining.

Summary

The following summarizes the major findings:

1. The specific concentrations of trace metals in dRDF-coal fly ash are similar to those found in pure coal fly ash. The dRDF is the primary source of Br, Mn, Pb, and Sb while the coal is the primary source of As, Ni, and V.

2. Several metals, particulary As, Ga, Na, and Sb, tend to concentrate in small particles.

3. The volatization-condensation process which deposits volatile metals onto small fly ash particles is more effective in a plant firing a dRDF-coal mixture than in a plant firing coal only. The greater volatile metal deposits in the coal-dRDF firing were probably due to the low combustion temperatures.

4. Except for Ni and P, the metals in the coal-dRDF fly ash increase in solubility with increasing dRDF content.

5. Both trace and matrix metals have a significantly greater solubility in small particles than in large particles.

In summary, the results from the trace compound emissions test results indicate that the quantities of the trace organic emissions for the blends studied were so small that the ground-level concentrations would probably not exceed 1 percent of the threshold level limits. Hence, unless the data from future tests indicate higher levels of trace organics, the emission levels from coal-dRDF firings would be within acceptable limits. The quantities of metals present in the fly ash and bottom ash suggest that further studies need to be carried out to establish if there is a health hazard due to (1) increased bulk solubility (as well as greater trace metal mobilization) of bottom ash with increased dRDF substitution and (2) the adsorption of volatilized metals during combustion onto the surface area of small (aerosol size) particulates.

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APPENDIX A
EMISSIONS, FUEL, AND ASH DATA SUMMARIES

TABLE A-1. FIELD TEST RESULTS FOR COAL ONLY 1:0 FIRING

				PPM														
DATE	$\mathcal{L}$	GR/SCF	BOILER	Cl	F	SO$_x$M	SO$_x$WC	NO$_x$M	NO$_x$WC	THC	% EA	% OPACITY	PPM SO$_3$	g/hr REINJECT	g/hr COLLECT	Ω-CM RESIS.	°F T_{flame}	°F T_{flue}
3/19	.51	.311	1	72	8		2312		332									411
3/19	.51	.458	1	84	15		1691											410ℓ^1/502ℓ^2
3/21	.40	.267	2			1397		362		21.9	104	38				<10^7		510#^{2}
3/21	.40	.325	2	75	7.2						104	38				<10^7		509#^{2}
3/22	.40	.226	1	55	7.3		1397	257		12.7	72	32		110		<10^7	2201	395ℓ^1
3/28	.38	.197	1	38	9.3		1153	197		13.7	92	44		110			2236	403
3/31	.27	.286	1	35	8.1	1000	1040	277			71	68		76			2210	399
3/31	.27	.234	1	36	6.5		1117			29.6	71	68		76			2197	404
4/1	.35	.281	1	44	7.5	1148	1324	300		34.1	82	46		75			2259	418
5/3	.25	.295	2	25	5.4	1118	1125	221	306		72	50		82	103		2209	484
5/4	.20	.339	2	19	7.9	1495		136			116	70		102	140		2121	459
5/4	.22		2			1080					106	70	20.7	152	90		2020	454
5/5	.31	.206	2			283		101	229		84	54		70	106		2244	491
5/5	.51	.199	2	19	6.8	367	541				40	54		99	123		2440	490
5/16	.21	.588	2	25	11.9	1302	1341	408	432	19.2	147	70		252 (0.10)	592 (0.14)		2125	474
5/16	.36	.298	2	26	7.8	1083	1121				104	70		235 (0.12)	579 (0.14)		2302	517
5/17	.17	.448	2			1254					96	91		491 (0.10)	666 (0.17)		2024	461
5/17	.17		2			1118	1149					91	52					
1/20	.53	.330	1	27	25	1734	4888	348		12.0	108	39						430
1/20	.53	.436	1	32	46	1734	5946	348		8.8	88	42						424
1/21	.47	.214	1	14	16	1155	2329	221		12.6	86	37						427
1/24	.53	.327	1	31	16	1265	2217		412	1.8	87	41						
1/25	.50		1			1291			577	1.6	110	39						
12/10		.229	1	98	4.6	1916		251				59						
12/10		.240	1	115	23.6	1381						59						

NOTES:
1. All values adjusted to 50% EA or 12% CO$_2$.
2. GR/SCF is grains/standard ft^3.
3. Lined out data are considered outliers.
4. SO$_x$M is sulfur oxides measured with a meter (electrochemical transducer).
5. SO$_x$WC is sulfur oxides measured by wet chemistry.
6. In volumes headed by "g/hr," any second value (shown in parantheses) represents fly ash density in g/cc.

TABLE A-2. FIELD TEST RESULTS FOR 1:1 BLEND FIRING

				PPM							%	%	PPM	g/hr	g/hr	Ω-CM	°F	°F
DATE	ℒ	GR/SCF	BOILER	Cl	F	SO_xM	SO_xWC	NO_xM	NO_xWC	THC	EA	OPACITY	SO_3	REINJECT	COLLECT	RESIS.	T_{flame}	T_{flue}
3/23	.43	.138	1	311	9.1	652	794			8.3	74	27		87		1×10^{10}	2226	423
3/23	.43	.191	1	321	7.0		755			18.4	74	27		87		1×10^{10}	2213	429
3/24	.44	.196	1	265	13.7	1003	1118	248		13.4	102	22		82		4×10^{9}	2275	430
5/12	.34	.287	2	195	8.4	1388	1502	351	387		109	59		141 (0.15)	384 (0.20)	7×10^{9}	2305	506
5/12	.28	.303	2	172	7.4	1503	1476				109	59		117 (0.16	344 (0.18)	5×10^{9}	2264	493
5/13	.39	.191	2	146	11.8	1391	1268	436	415	20.0	101	42		131 (0.14)	669 (0.16)	3×10^{10}	2253	505
5/13	.30		2			1054	992				101	42	18.3	122 (0.14)	260 (0.17)	5×10^{10}	2210	497
12/8	.45	.172	1	281	27	1402		224		9.0		70						
12/13	.45	.441	1	437	22.3	1809		282	337			73						
12/13	.45	.224	1	182	33	1235						73						
12/14	.43	.196	1	58		808		278	225			74						
12/14	.43	.177	1	309		1234						74						

NOTE: See notes for Table A-1.

TABLE A-3. FIELD TEST RESULTS FOR 1:2 BLEND FIRING

				PPM							%	%	PPM	g/hr	g/hr	Ω-CM	°F	°F
DATE	∠	GR/SCF	BOILER	Cl	F	SO_xM	SO_xWC	NO_xM	NO_xWC	THC	EA	OPACITY	SO_3	REINJECT	COLLECT	RESIS.	T_{flame}	T_{flue}
3/29	.36	.203	1	438	14.0	800	994	219		19.7	94	31		82			2287	415
3/29	.36	.176	1	323	12.4		986			15.8	94	31		82			2306	409
3/30	.26	.180	1	301	8.8		461			34.2	91	42		98			2313	391
5/10	.36	.282	2	198	11.7	828	928	256	221		138	45		123 (0.17)	155 (0.21)	6×10^{11}	2401	515
5/10	.30	.320	2	238	11.1	980	810				116	45		133 (0.10)	164 (0.23)	8×10^{9}	2322	512
5/11	.36	.248	2	243	11.6	777	842	305	273	19.1	132	45		240 (0.20)	241 (0.27)	2×10^{12}	2308	518
5/11	.34		2			715	722				114	45	10.3	138 (0.17)	241 (0.26)	4×10^{11}	2299	506

NOTE: See notes for Table A-1.

TABLE A-4. FIELD TEST RESULTS FOR dRDF 0:1 FIRING

				PPM							%	%	PPM	g/hr	g/hr	Ω-CM	°F	°F
DATE	$\mathcal{L}$	GR/SCF	BOILER	Cl	F	SO_xM	SO_xWC	NO_xM	NO_xWC	THC	EA	OPACITY	SO_3	REINJECT	COLLECT	RESIS.	T_{flame}	T_{flue}
5/14	.27	.348	2	654	9.4	251	303	486	489	56.3	133	48		215 (0.85)	273 (0.76)	1×10^{12}	2326	470
5/14	.26	.356	2	610	7.8	275	268	456	441		106	48		230 (0.84)	271 (0.70)	1×10^{12}	2285	473

NOTE: See notes for Table A-1.

TABLE A-5. CORRECTED FIELD TEST RESULTS FOR FOUR COAL:dRDF BLENDS

(Emission data were normalized to the March reference coal)

					PPM					
BLEND	DATE		BOILER	ASH-GR/SCF	Cl	SO_xM	SO_xWC	THC	NO_xM	NO_xWC
1:0 (coal only)	3/19	.51	1	.311	72		2312			332
	3/19	.51	1	.458	84		1691			
	3/21	.40	2	.267		1397		21.9	362	
	3/21	.40	2	.325	75					
	3/22	.40	1	.226	55		1397	12.7	257	
	3/28	.38	1	.197	38		1153	13.7	197	
	3/31	.27	1	.286	35	1000	1040		277	
	3/31	.27	1	.234	36		1117	29.6		
	4/1	.35	1	.281	44	1148	1324	34.1	300	
	5/3	.25	2	.124	50	1375	1384		230	318
	5/4	.20	2	.142	38	1839			141	
	5/4	.22	2			1328				
	5/5	.31	2	.087		348			105	238
	5/5	.51	2	.084	38	451	665			
	5/16	.21	2	.247	50	1601	1649	17.3	424	449
	5/16	.36	2	.125	52	1332	1379			
	5/17	.17	2	.188		1542				
	5/17	.17	2			1375	1413			
	1/20	.53	1	.238	11	1266	~~3568~~*	13.1	358	
	1/20	.53	1	.314	13	1266	~~4341~~	9.6	358	
	1/21	.47	1	.154	6	843	1700	13.7	228	
	1/24	.53	1	.235	12	923	1618	2.0		424
	1/25	.50	1			942		1.7		594
	12/10		1	.165	39	1399			259	
	12/10		1	.173	46	1008				
1:1	3/23	.43	1	.137	280	652	794	8.1		
	3/23	.43	1	.189	289		755	18.0		
	3/24	.44	1	.194	239	1003	1118	13.1	255	
	5/12	.34	2	.161	234	1693	1832		326	360
	5/12	.28	2	.170	206	1834	1801			
	5/13	.39	2	.107	175	1697	1547	18.8	405	386
	5/13	.30	2			1286	1210			
	12/8	.45	1	.196	202	715		8.1	302	
	12/13	.45	1	.503	315	923			381	455
	12/13	.45	1	.255	131	630				
	12/14	.43	1	.223	42	412			375	304
	12/14	.43	1	.202	222	629				
1:2	3/29	.36	1	.201	407	808	1004	19.3	232	
	3/29	.36	1	.174	300		996	15.5		
	3/30	.26	1	.178	280		466	33.5		
	5/10	.36	2	.175	216	994	1114		223	192
	5/10	.30	2	.198	259	1176	972			
	5/11	.36	2	.154	265	932	1010	18.3	265	238
	5/11	.34	2			858	866			
0:1 (dRDF only)	5/14	.27	2	.268	654	251	303	55.7	272	274
	5/14	.26	2	.274	610	275	268		255	247

*Outliers were omitted from statistical analysis.

TABLE A-6. AS-RECEIVED COAL PROPERTIES

DATE	DEC	JAN	JAN	JAN	JAN AVERAGE	MARCH	MARCH	MARCH	MARCH	MARCH* AVERAGE	MAY	MAY	MAY	MAY AVERAGE
As Received														
% Moisture	2.12	8.00	10.80	2.30	7.03	4.92	4.00	2.20	4.00	3.78	1.46	1.00	1.35	1.27
% Ash	10.78	11.78	15.87	15.24	14.30	10.50	10.70	10.50	9.20	10.23	22.15	28.27	15.43	21.95
% Volatile	29.42	18.33	15.73	14.43	16.16	30.38	19.87	18.60	20.85	22.43	23.45	16.91	27.29	22.55
% Fixed C.	57.68	61.89	57.60	68.03	62.50	54.20	65.43	68.60	65.95	63.55	52.94	53.82	55.93	54.23
Btu/lb	13,471	12,100	10,910	12,380	11,797	12,675	12,780	13,210	13,170	12,959	11,603	10,800	12,715	11,706
Dry Basis														
% C	77.15	72.7	69.2	69.6	70.5	75.21	73.1	73.9	74.4	74.15	66.82	63.10	72.28	67.4
% H	4.77	4.1	3.8	3.5	3.8	4.90	4.2	4.1	4.3	4.38	4.48	3.77	4.74	4.33
% N_2	1.26	1.6	1.5	1.6	1.57	1.34	1.6	1.7	1.7	1.59	1.15	1.21	1.69	1.35
% Cl	.26	--	--	--		.06	.14	.14	.11	.11	.08	.03	.05	.05
% S	3.57	1.70	1.1	2.6	1.80	1.58	1.90	1.60	1.80	1.72	1.01	1.09	1.56	1.22
% Ash	11.01	12.81	17.79	15.60	15.40	11.04	11.14	10.74	9.58	10.63	22.48	28.56	15.64	22.23
% O_2	1.98	7.1	6.6	7.1	6.93	5.87	8.0	7.9	8.2	7.42	3.98	2.24	4.04	3.42
Fusion														
Initial	2060°F	2460°F	2540°F	2280°F	2427°F	2330°F	2340°F	2330°F	2300°F	2325°F	2700+°F	2700+°F	2700+°F	2700+°F
1st Softening	2180°F	2540°F	2610°F	2340°F	2497°F	2385°F	2400°F	2400°F	2360°F	2386°F	2700+°F	2700+°F	2700+°F	2700+°F
2nd Softening	2280°F	2500°F	2660°F	2390°F	2517°F	2430°F	2450°F	2460°F	2400°F	2435°F	2700+°F	2700+°F	2700+°F	2700+°F
Fluid	2500°F	2570°F	2720°F	2440°F	2577°F	2525°F	2500°F	2520°F	2450°F	2499°F	2700+°F	2700+°F	2700+°F	2700+°F
Mineral Analysis														
Phos.Pent Ox.	.48	.92			.92	.41				.41		.30	.35	.33
Silica	35.43	43.50			43.50	52.05				52.02		62.23	57.00	59.62
Ferric Ox.	34.94	21.00			21.00	12.74				12.74		3.83	7.76	5.80
Alumina	22.39	20.70			20.70	25.64				25.64		26.83	28.02	27.43
Titania	.56	1.42			1.42	.70				.70		.89	.91	.90
Sodium Ox.	.25	2.70			2.70	.47				.47		.27	.34	.31
Potasium Ox.	.99	2.37			2.37	1.87				1.87		2.52	2.12	2.32
Lime	1.63	.38			.38	2.18				2.18		.43	.64	.54
Magnesia	.28	.58			.58	.36				.36		1.19	1.10	1.15
Sulfur TriOx.	1.23	.83			.83	1.66				1.66		.02	.62	.32
Undet.	1.82					1.95				1.95		1.49	1.14	1.32

TABLE A-7. MOISTURE AND ASH FREE COAL PROPERTIES

	DEC	JAN	JAN	JAN	JAN AVERAGE	MARCH	MARCH	MARCH	MARCH	MARCH AVERAGE	MAY	MAY	MAY	MAY AVERAGE
% Moisture	0	0	0	0	0	0	0	0	0	0	0	0	0	0
% Ash	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Btu/lb	13,471	12,100	10,910	12,380	11,797	12,675	12,780	13,210	13,170	12,959	11,603	10,800	12,715	11,706
MAF Basis														
% Vol	33.78	22.85	21.45	17.50	20.6	35.92	23.29	21.31	24.02	26.14	30.70	23.90	32.80	29.13
% Fixed C.	66.22	77.15	78.55	82.50	79.4	64.08	76.71	78.58	75.98	73.84	69.30	76.10	67.20	70.87
Btu/lb	15,466	15,084	14,878	15,013	14,996	14,986	14,982	15,132	15,173	15,063	15,189	15,270	15,279	15,246
% C	86.70	83.38	84.18	82.46	83.34	84.55	82.27	82.79	82.29	82.98	86.20	88.32	85.68	86.73
% H	5.36	4.70	4.62	4.15	4.49	5.51	4.73	4.59	4.76	4.90	5.78	5.28	5.62	5.56
% N	1.42	1.83	1.82	1.90	1.85	1.51	1.80	1.90	1.88	1.77	1.48	1.69	2.00	1.72
% Cl	.29	--	--			.07	.16	.16	.12	.13	.10	.04	.06	.07
% S	4.01	1.95	1.34	3.08	2.12	1.78	2.14	1.79	1.99	1.93	1.30	1.53	1.45	1.43
% O_2	2.23	8.14	8.03	8.41	8.19	6.60	9.00	8.85	9.07	8.38	5.13	3.14	4.79	4.35

Note: Used as the reference fuel.

TABLE A-8. AS-RECEIVED dRDF PROPERTIES

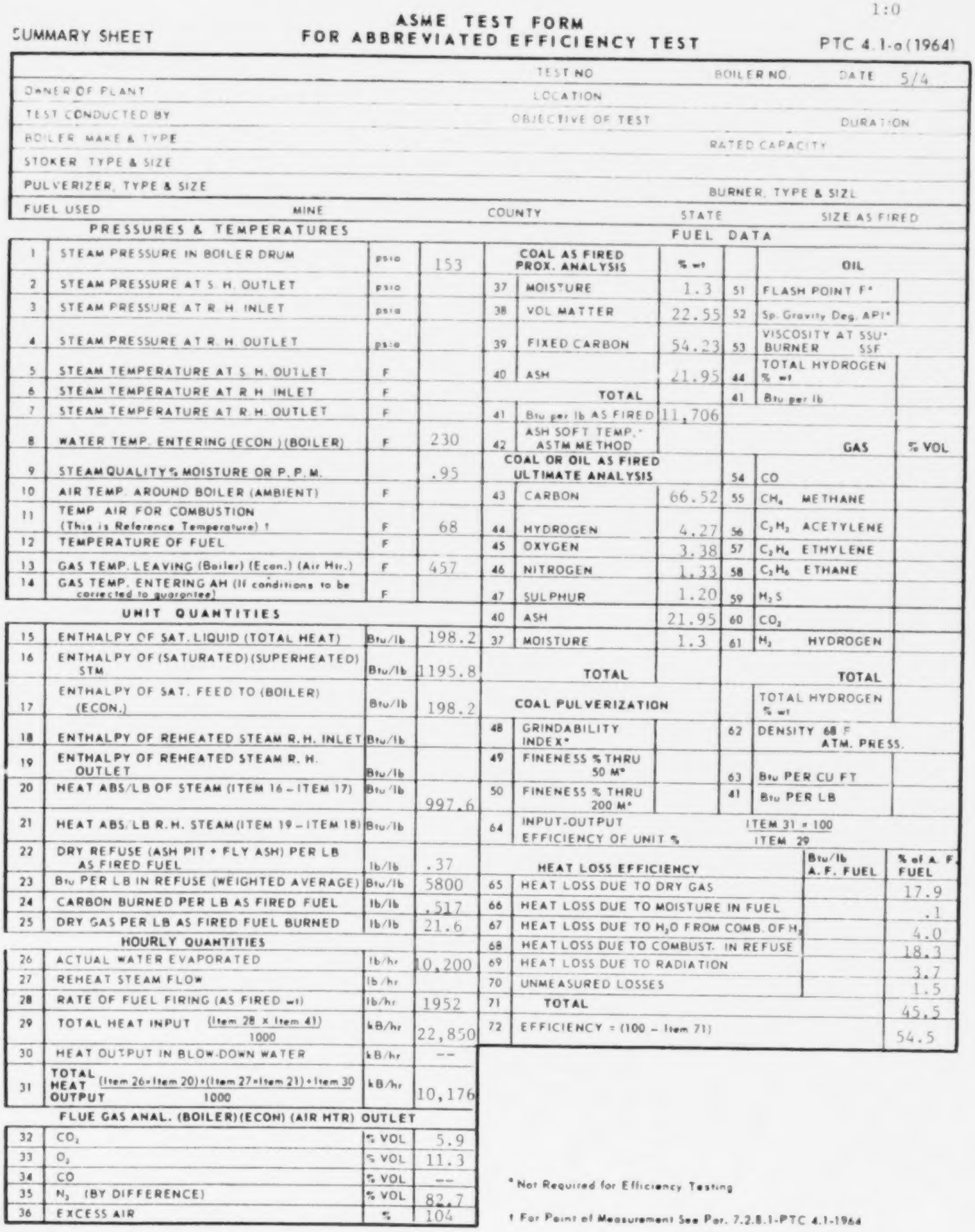
	DEC	DEC	DEC AVERAGE	MARCH	MARCH	MARCH	MARCH	MARCH AVERAGE	MAY	MAY	MAY	MAY AVERAGE	*GRAND AVERAGE
As Received													
% Moisture	10.72	16.08	13.4	9.55	15.69			12.62	7.00	13.15	16.51	12.22	12.75
% Ash	16.95	22.98	19.97	24.55	24.28			24.41	23.51	30.04	32.72	28.75	24.38
% Volatile	59.89	53.18	56.54	57.84	50.32			54.08	58.42	47.57	41.81	49.27	53.30
% Fixed C.	12.44	7.76	10.1	8.06	9.71			8.89	11.07	9.24	8.96	9.76	9.58
Btu/lb	6667	6309	6488	6008	5059			5534	6015	5068	4716	5266	5763
Dry Basis													
% C	43.98		43.98	37.04	41.3			39.17	38.48	34.04	34.38	35.63	39.59
% H	5.29		5.29	5.04	3.9			4.47	5.38	4.27	3.96	4.54	4.77
% N_2	.35		.35	.47	.30			.39	1.23	.58	.73	.85	.53
% Cl	.40		.40	.49	.40			.45	.31	.32	.44	.36	.40
% S	.19	.60	.40	.22	.30			.26	.19	.27	.37	.28	.31
% Ash	18.99	27.38	23.19	27.14	28.80			27.97	25.28	34.59	39.19	33.02	28.06
% O_2	30.80		30.80	29.60	25.00			27.30	29.13	25.93	20.93	25.33	27.81
Fusion													
Initial	1955°F	2080°F	2018°F	1940°F	2080°F	2080°F	2060°F	2040°F	1960°F	2050°F		2005°F	
1st Softening	2055°F	2120°F	2088°F	2000°F	2160°F	2130°F	2120°F	2103°F	2060°F	2150°F		2105°F	
2nd Softening	2175°F		2175°F	2060°F	2210°F	2170°F	2180°F	2155°F	2080°F	2170°F		2125°F	
Fluid	2290°F	2260°F	2275°F	2180°F	2260°F	2200°F	2220°F	2215°F	2190°F	2260°F		2225°F	
Mineral Analysis													
Phos.Pent.Ox	.87		.87	.67		.71	.82	.73	.73	.58	.64	.65	
Silica	55.52		55.52	64.29		77.45	73.00	71.58	63.06	63.58	64.31	63.65	
Ferric Ox.	2.27		2.27	2.34		1.91	4.41	2.89	1.57	4.27	2.09	2.64	
Alumina	13.45		13.45	6.74		2.77	3.78	4.43	6.43	12.23	6.52	8.39	
Titania	.66		.66	.55		1.10	1.33	.99	.56	.73	.79	.69	
Sodium Ox.	6.82		6.82	9.60		1.46	5.93	5.66	9.69	5.81	7.08	7.53	
Potasium Ox.	1.30		1.30	.60		.34	.65	.53	.65	1.22	.86	.91	
Lime	10.75		10.75	10.08		6.90	5.54	7.50	10.54	7.82	10.87	9.74	
Magnesium	1.14		1.14	1.77		.81	.77	1.12	1.71	1.54	1.51	1.59	
Sulfur TriOx.	6.03		6.03	1.49		1.13	1.03	1.22	3.60	.93	5.08	3.20	
Undet.	1.19		1.19	1.87				1.87	1.46	1.29	.25	1.00	

Note: The d-RDF properties (grand average) were used as a basis for normalizing the emissions results for all test data.

TABLE A-9. MOISTURE AND ASH FREE dRDF PROPERTIES

	DEC	DEC	MARCH	MARCH	MAY	MAY	MAY	AVERAGE	S.D.
% Moisture	0	0	0	0	0	0	0	0	--
% Ash	0	0	0	0	0	0	0	0	--
Btu/lb	6667	6309	6008	5059	6015	5068	4716	5692	739
MAF Basis									
% Vol	82.80	87.27	87.77	83.82	84.07	83.73	82.35	84.54	2.13
% Fixed C.	17.20	12.73	12.23	16.18	15.93	16.27	17.65	15.46	2.13
Btu/lb	9217	10353	9117	8427	8656	8921	9290	9140	618
% C	54.29		50.84	58.00	51.50	52.04	56.54	53.87	2.92
% H	6.53		6.92	5.48	7.20	6.53	6.51	6.53	.58
% N_2	.43		.65	.42	1.65	.89	1.20	.87	.48
% Cl	.49		.67	.56	.41	.49	.72	.56	.12
% S	.23	.83	.30	.42	.25	.41	.61	.44	.22
% O_2	38.02		40.63	35.11	38.99	39.64	34.42	37.80	2.51

APPENDIX B
SUMMARY SHEETS FOR ASME ABBREVIATED EFFICIENCY TESTS AND BOILERS 1 AND 2 SPECIFICATIONS



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SUMMARY SHEET

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

PTC 4.1-a (1964)

	TEST NO	BOILER NO.	DATE 5/4
OWNER OF PLANT	LOCATION		
TEST CONDUCTED BY	OBJECTIVE OF TEST		DURATION
BOILER MAKE & TYPE		RATED CAPACITY	
STOKER TYPE & SIZE			
PULVERIZER, TYPE & SIZE		BURNER, TYPE & SIZE	
FUEL USED	MINE	COUNTY	STATE	SIZE AS FIRED

PRESSURES & TEMPERATURES

1	STEAM PRESSURE IN BOILER DRUM	psia	153
2	STEAM PRESSURE AT S. H. OUTLET	psia	
3	STEAM PRESSURE AT R. H. INLET	psia	
4	STEAM PRESSURE AT R. H. OUTLET	psia	
5	STEAM TEMPERATURE AT S. H. OUTLET	F	
6	STEAM TEMPERATURE AT R. H. INLET	F	
7	STEAM TEMPERATURE AT R. H. OUTLET	F	
8	WATER TEMP. ENTERING (ECON.) (BOILER)	F	230
9	STEAM QUALITY % MOISTURE OR P. P. M.		.95
10	AIR TEMP. AROUND BOILER (AMBIENT)	F	
11	TEMP AIR FOR COMBUSTION (This is Reference Temperature) †	F	68
12	TEMPERATURE OF FUEL	F	
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F	457
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F	

UNIT QUANTITIES

15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb	198.2
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM	Btu/lb	1195.8
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb	198.2
18	ENTHALPY OF REHEATED STEAM R.H. INLET	Btu/lb	
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb	
20	HEAT ABS/LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb	997.6
21	HEAT ABS/LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb	
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb	.37
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb	5800
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb	.517
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb	21.6

HOURLY QUANTITIES

26	ACTUAL WATER EVAPORATED	lb/hr	10,200
27	REHEAT STEAM FLOW	lb/hr	
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr	1952
29	TOTAL HEAT INPUT $\frac{(\text{Item 28} \times \text{Item 41})}{1000}$	kB/hr	22,850
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr	--
31	TOTAL HEAT OUTPUT $\frac{(\text{Item 26} \times \text{Item 20}) + (\text{Item 27} \times \text{Item 21}) + \text{Item 30}}{1000}$	kB/hr	10,176

FLUE GAS ANAL. (BOILER) (ECON) (AIR HTR) OUTLET

32	CO_2	% VOL	5.9
33	O_2	% VOL	11.3
34	CO	% VOL	--
35	N_2 (BY DIFFERENCE)	% VOL	82.7
36	EXCESS AIR	%	104

FUEL DATA

COAL AS FIRED PROX. ANALYSIS		% wt
37	MOISTURE	1.3
38	VOL MATTER	22.55
39	FIXED CARBON	54.23
40	ASH	21.95
	TOTAL	
41	Btu per lb AS FIRED	11,706
42	ASH SOFT TEMP.* ASTM METHOD	

OIL		
51	FLASH POINT F*	
52	Sp. Gravity Deg. API*	
53	VISCOSITY AT BURNER SSU* SSF	
44	TOTAL HYDROGEN % wt	
41	Btu per lb	

COAL OR OIL AS FIRED ULTIMATE ANALYSIS		
43	CARBON	66.52
44	HYDROGEN	4.27
45	OXYGEN	3.38
46	NITROGEN	1.33
47	SULPHUR	1.20
40	ASH	21.95
37	MOISTURE	1.3
	TOTAL	

	GAS	% VOL
54	CO	
55	CH_4 METHANE	
56	C_2H_2 ACETYLENE	
57	C_2H_4 ETHYLENE	
58	C_2H_6 ETHANE	
59	H_2S	
60	CO_2	
61	H_2 HYDROGEN	
	TOTAL	
	TOTAL HYDROGEN % wt	
62	DENSITY 68 F ATM. PRESS.	
63	Btu PER CU FT	
41	Btu PER LB	

COAL PULVERIZATION		
48	GRINDABILITY INDEX*	
49	FINENESS % THRU 50 M*	
50	FINENESS % THRU 200 M*	

64	INPUT-OUTPUT EFFICIENCY OF UNIT %	$\frac{\text{ITEM 31} \times 100}{\text{ITEM 29}}$

HEAT LOSS EFFICIENCY		Btu/lb A. F. FUEL	% of A. F. FUEL
65	HEAT LOSS DUE TO DRY GAS		17.9
66	HEAT LOSS DUE TO MOISTURE IN FUEL		.1
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2		4.0
68	HEAT LOSS DUE TO COMBUST. IN REFUSE		18.3
69	HEAT LOSS DUE TO RADIATION		3.7
70	UNMEASURED LOSSES		1.5
71	TOTAL		45.5
72	EFFICIENCY = (100 – Item 71)		54.5

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

1:0
PTC 4.1-b (1964)

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

CALCULATION SHEET

Revised September, 1965

	OWNER OF PLANT · TEST NO · BOILER NO. · DATE			
30	HEAT OUTPUT IN BOILER BLOW-DOWN WATER = LB OF WATER BLOWDOWN PER HR × $\left[\frac{\text{ITEM 15} - \text{ITEM 17}}{1000}\right]$ = ... kB/hr			
24	*If impractical to weigh refuse, this item can be estimated as follows* DRY REFUSE PER LB OF AS FIRED FUEL = $\frac{\overset{21.95}{\text{\% ASH IN AS FIRED COAL}}}{\underset{.40}{100 - \text{\% COMB. IN REFUSE SAMPLE}}}$ CARBON BURNED PER LB AS FIRED FUEL = $\frac{\overset{66.52}{\text{ITEM 43}}}{100} - \left[\frac{\overset{.37}{\text{ITEM 22}} \times \overset{5800}{\text{ITEM 23}}}{14{,}500}\right] = .517$ NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.			
25	DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)} \times (\text{LB CARBON BURNED PER LB AS FIRED FUEL} + \frac{3}{8}S)$ $= \frac{11 \times \overset{\text{ITEM 32}}{5.9} + 8 \times \overset{\text{ITEM 33}}{11.3} + 7\left(\overset{\text{ITEM 35}}{82.7} + \overset{\text{ITEM 34}}{--}\right)}{3 \times \left(\overset{\text{ITEM 32}}{5.9} + \overset{\text{ITEM 34}}{--}\right)} \times \left[\overset{\text{ITEM 24}}{.517} + \frac{\overset{\text{ITEM 47}}{1.2}}{267}\right] = 21.6$			
36	EXCESS AIR † = $100 \times \frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})} = 100 \times \frac{\overset{11.3}{\text{ITEM 33}} - \frac{\text{ITEM 34}}{2}}{.2682\,(\overset{82.7}{\text{ITEM 35}}) - (\overset{11.3}{\text{ITEM 33}} - \frac{\text{ITEM 34}}{2})} = 104\%$			
	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	$\frac{\text{LOSS}}{\text{HHV}} \times 100 =$	LOSS %
65	HEAT LOSS DUE TO DRY GAS = LB DRY GAS PER LB AS FIRED FUEL $\times \overset{.25}{C_p} \times (t_{lvg} - t_{air}) = \underset{21.6}{\text{ITEM 25}} \times \overset{0.25}{\cancel{XXX}} \, (\underset{457}{\text{ITEM 13}}) - (\underset{68}{\text{ITEM 11}}) = \ldots\ldots$	2101	$\frac{65}{41} \times 100 =$	17.9
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $\frac{\text{ITEM 37}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) 1269 − (ENTHALPY OF LIQUID AT T ITEM 11) 36] = ...	16.0	$\frac{66}{41} \times 100 =$	.1
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $9 \times \frac{\overset{4.27}{\text{ITEM 44}}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	474	$\frac{67}{41} \times 100 =$	4.0
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = $\overset{\text{ITEM 22}}{.37} \times \overset{\text{ITEM 23}}{5800}$ = ...	2146	$\frac{68}{41} \times 100 =$	18.3
69	HEAT LOSS DUE TO RADIATION* = $\frac{\text{TOTAL BTU RADIATION LOSS PER HR}}{\text{LB AS FIRED FUEL} \quad \text{ITEM 28}}$	......	$\frac{69}{41} \times 100 =$	3.7
70	UNMEASURED LOSSES **	......	$\frac{70}{41} \times 100 =$	1.5
71	TOTAL	......	......	45.5
72	EFFICIENCY = (100 − ITEM 71)	......	......	54.5

† For rigorous determination of excess air see Appendix 9.2 – PTC 4.1-1964

* If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may by provided for by assigning a mutually agreed upon value for Item 70.

SUMMARY SHEET

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

1:1

PTC 4.1-a(1964)

	TEST NO	BOILER NO	DATE 5/13
OWNER OF PLANT	LOCATION		
TEST CONDUCTED BY	OBJECTIVE OF TEST		DURATION
BOILER MAKE & TYPE		RATED CAPACITY	
STOKER TYPE & SIZE			
PULVERIZER, TYPE & SIZE		BURNER, TYPE & SIZE	
FUEL USED MINE	COUNTY	STATE	SIZE AS FIRED

PRESSURES & TEMPERATURES

1	STEAM PRESSURE IN BOILER DRUM	psia	155
2	STEAM PRESSURE AT S. H. OUTLET	psia	
3	STEAM PRESSURE AT R. H. INLET	psia	
4	STEAM PRESSURE AT R. H. OUTLET	psia	
5	STEAM TEMPERATURE AT S. H. OUTLET	F	
6	STEAM TEMPERATURE AT R. H. INLET	F	
7	STEAM TEMPERATURE AT R. H. OUTLET	F	
8	WATER TEMP. ENTERING (ECON.)(BOILER)	F	221
9	STEAM QUALITY % MOISTURE OR P. P. M.		.95
10	AIR TEMP. AROUND BOILER (AMBIENT)	F	
11	TEMP. AIR FOR COMBUSTION (This is Reference Temperature) †	F	78
12	TEMPERATURE OF FUEL	F	--
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F	501
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F	

UNIT QUANTITIES

15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb	
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM	Btu/lb	1196
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb	189
18	ENTHALPY OF REHEATED STEAM R. H. INLET	Btu/lb	
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb	
20	HEAT ABS/LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb	1007
21	HEAT ABS/LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb	
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb	.36
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb	5075
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb	.41
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb	12.62

HOURLY QUANTITIES

26	ACTUAL WATER EVAPORATED	lb/hr	20,018
27	REHEAT STEAM FLOW	lb/hr	--
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr	3309
29	TOTAL HEAT INPUT $\frac{\text{(Item 28} \times \text{Item 41)}}{1000}$	kB/hr	29,741
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr	--
31	TOTAL HEAT OUTPUT $\frac{\text{(Item 26} \times \text{Item 20)} + \text{(Item 27} \times \text{Item 21)} + \text{Item 30}}{1000}$	kB/hr	20,158

FLUE GAS ANAL. (BOILER) (ECON) (AIR HTR) OUTLET

32	CO_2	% VOL	8.1
33	O_2	% VOL	9.9
34	CO	% VOL	--
35	N_2 (BY DIFFERENCE)	% VOL	82.0
36	EXCESS AIR	%	82

FUEL DATA

COAL AS FIRED PROX. ANALYSIS		% wt	OIL		
37	MOISTURE	6.62	51	FLASH POINT F*	
38	VOL MATTER	31.68	52	Sp. Gravity Deg. API*	
39	FIXED CARBON	38.39	53	VISCOSITY AT SSU* BURNER SSF	
40	ASH	23.33	44	TOTAL HYDROGEN % wt	
	TOTAL		41	Btu per lb	
41	Btu per lb AS FIRED	89.88			
42	ASH SOFT TEMP.* ASTM METHOD				

COAL OR OIL AS FIRED ULTIMATE ANALYSIS			GAS		% VOL
			54	CO	
43	CARBON	54.06	55	CH_4 METHANE	
44	HYDROGEN	4.10	56	C_2H_2 ACETYLENE	
45	OXYGEN	9.83	57	C_2H_4 ETHYLENE	
46	NITROGEN	1.06	58	C_2H_6 ETHANE	
47	SULPHUR	.86	59	H_2S	
40	ASH	23.33	60	CO_2	
37	MOISTURE	6.62	61	H_2 HYDROGEN	
	TOTAL			TOTAL	

COAL PULVERIZATION					
				TOTAL HYDROGEN % wt	
48	GRINDABILITY INDEX*		62	DENSITY 68 F ATM. PRESS.	
49	FINENESS % THRU 50 M*		63	Btu PER CU FT	
50	FINENESS % THRU 200 M*		41	Btu PER LB	

64	INPUT-OUTPUT EFFICIENCY OF UNIT %	$\frac{\text{ITEM 31} \times 100}{\text{ITEM 29}}$

HEAT LOSS EFFICIENCY		Btu/lb A. F. FUEL	% of A. F. FUEL
65	HEAT LOSS DUE TO DRY GAS		14.8
66	HEAT LOSS DUE TO MOISTURE IN FUEL		.9
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2		5.1
68	HEAT LOSS DUE TO COMBUST. IN REFUSE		20.3
69	HEAT LOSS DUE TO RADIATION		1.8
70	UNMEASURED LOSSES		1.5
71	TOTAL		44.4
72	EFFICIENCY = (100 – Item 71)		55.6

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

PTC 4.1-b (1964) 1:1

ASME TEST FORM
CALCULATION SHEET **FOR ABBREVIATED EFFICIENCY TEST** *Revised September, 1965*

	OWNER OF PLANT	TEST NO.	BOILER NO.	DATE

30	HEAT OUTPUT IN BOILER BLOWDOWN WATER = LB OF WATER BLOWDOWN PER HR × $\left[\frac{\text{ITEM 15} - \text{ITEM 17}}{1000}\right]$ = kB/hr
24	*If impractical to weigh refuse, this item can be estimated as follows* DRY REFUSE PER LB OF AS FIRED FUEL = $\frac{\overset{23.33}{\text{\% ASH IN AS FIRED COAL}}}{\underset{.35}{\text{100 − \% COMB. IN REFUSE SAMPLE}}}$ CARBON BURNED PER LB AS FIRED FUEL = $\frac{\overset{\text{ITEM 43}}{5406}}{100} - \left[\frac{\overset{\text{ITEM 22}}{.36} \times \overset{\text{ITEM 23}}{4205}}{14{,}500}\right] = .41$ NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.
25	DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)} \times$ (LB CARBON BURNED PER LB AS FIRED FUEL + $\frac{3}{8}$ S) $= \frac{11 \times \overset{\text{ITEM 32}}{8.1} + 8 \times \overset{\text{ITEM 33}}{9.9} + 7\left(\overset{\text{ITEM 35}}{82} + \overset{\text{ITEM 34}}{---}\right)}{3 \times \left(\overset{\text{ITEM 32}}{8.1} + \overset{\text{ITEM 34}}{--}\right)} \times \left[\overset{\text{ITEM 24}}{.91} + \frac{\overset{\text{ITEM 47}}{.86}}{267}\right] = 12.62$
36	EXCESS AIR† $= 100 \times \frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})} = 100 \times \frac{\underset{9.9}{\text{ITEM 33}} - \frac{\text{ITEM 34}}{2}}{.2682\,(\underset{82}{\text{ITEM 35}}) - (\underset{9.9}{\text{ITEM 33}} - \frac{\text{ITEM 34}}{2})} = 82\%$

	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	$\frac{\text{LOSS}}{\text{HHV}} \times 100 =$	LOSS %
65	HEAT LOSS DUE TO DRY GAS = LB DRY GAS PER LB AS FIRED FUEL $\times C_p \times (t_{lvg} - t_{air})$ = $\underset{12.62}{\text{ITEM 25}} \times 0.25 \times [\overset{501}{\text{(ITEM 13)}} - \overset{78}{\text{(ITEM 11)}}]$ =	1335	$\frac{65}{41} \times 100 =$	14.8
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $\frac{\overset{6.62}{\text{ITEM 37}}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) 1288.3 − (ENTHALPY OF LIQUID AT T ITEM 11) 46] =	82	$\frac{66}{41} \times 100 =$	.9
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $9 \times \frac{\overset{4.1}{\text{ITEM 44}}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] =	458	$\frac{67}{41} \times 100 =$	5.1
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = $\overset{\text{ITEM 22}}{.36} \times \overset{\text{ITEM 23}}{5075}$ =	1827	$\frac{68}{41} \times 100 =$	20.3
69	HEAT LOSS DUE TO RADIATION* = $\frac{\text{TOTAL BTU RADIATION LOSS PER HR}}{\text{LB AS FIRED FUEL} \quad \text{ITEM 28}}$		$\frac{69}{41} \times 100 =$	1.8
70	UNMEASURED LOSSES **		$\frac{70}{41} \times 100 =$	1.5
71	TOTAL			44.4
72	EFFICIENCY = (100 − ITEM 71)			55.6

† For rigorous determination of excess air see Appendix 9.2 – PTC 4.1-1964

* If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may by provided for by assigning a mutually agreed upon value for Item 70.

1:2

SUMMARY SHEET

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

PTC 4.1-a(1964)

TEST NO BOILER NO DATE 5/11
OWNER OF PLANT LOCATION
TEST CONDUCTED BY OBJECTIVE OF TEST DURATION
BOILER MAKE & TYPE RATED CAPACITY
STOKER TYPE & SIZE
PULVERIZER, TYPE & SIZE BURNER, TYPE & SIZE
FUEL USED MINE COUNTY STATE SIZE AS FIRED

PRESSURES & TEMPERATURES

1	STEAM PRESSURE IN BOILER DRUM	psia	154
2	STEAM PRESSURE AT S. H. OUTLET	psia	
3	STEAM PRESSURE AT R. H. INLET	psia	
4	STEAM PRESSURE AT R. H. OUTLET	psia	
5	STEAM TEMPERATURE AT S. H. OUTLET	F	
6	STEAM TEMPERATURE AT R. H. INLET	F	
7	STEAM TEMPERATURE AT R. H. OUTLET	F	
8	WATER TEMP. ENTERING (ECON.)(BOILER)	F	230
9	STEAM QUALITY % MOISTURE OR P. P. M.		.95
10	AIR TEMP. AROUND BOILER (AMBIENT)	F	
11	TEMP. AIR FOR COMBUSTION (This is Reference Temperature) †	F	70
12	TEMPERATURE OF FUEL	F	--
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F	512
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F	

UNIT QUANTITIES

15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb	
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM	Btu/lb	1195.8
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb	198.2
18	ENTHALPY OF REHEATED STEAM R.H. INLET	Btu/lb	
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb	
20	HEAT ABS/LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb	997.6
21	HEAT ABS/LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb	
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb	.35
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb	4205
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb	.371
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb	14.3

HOURLY QUANTITIES

26	ACTUAL WATER EVAPORATED	lb/hr	17,738
27	REHEAT STEAM FLOW	lb/hr	
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr	3776
29	TOTAL HEAT INPUT $\frac{\text{(Item 28 × Item 41)}}{1000}$	kB/hr	30,684
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr	--
31	TOTAL HEAT OUTPUT $\frac{\text{(Item 26×Item 20)+(Item 27×Item 21)+Item 30}}{1000}$	kB/hr	17,696

FLUE GAS ANAL. (BOILER)(ECON) (AIR HTR) OUTLET

32	CO_2	% VOL	6.4
33	O_2	% VOL	11.0
34	CO	% VOL	--
35	N_2 (BY DIFFERENCE)	% VOL	82.6
36	EXCESS AIR	%	98.6

FUEL DATA

	COAL AS FIRED PROX. ANALYSIS	% wt		OIL	
37	MOISTURE	7.94	51	FLASH POINT F*	
38	VOL MATTER	38.26	52	Sp. Gravity Deg. API*	
39	FIXED CARBON	29.09	53	VISCOSITY AT BURNER SSU* SSF	
40	ASH	24.73	44	TOTAL HYDROGEN % wt	
	TOTAL		41	Btu per lb	
41	Btu per lb AS FIRED	83.82			
42	ASH SOFT TEMP. ASTM METHOD			GAS	% VOL

	COAL OR OIL AS FIRED ULTIMATE ANALYSIS				
			54	CO	
43	CARBON	47.29	55	CH_4 METHANE	
44	HYDROGEN	4.07	56	C_2H_2 ACETYLENE	
45	OXYGEN	14.19	57	C_2H_4 ETHYLENE	
46	NITROGEN	.90	58	C_2H_6 ETHANE	
47	SULPHUR	.66	59	H_2S	
40	ASH	24.73	60	CO_2	
37	MOISTURE	7.94	61	H_2 HYDROGEN	
	TOTAL			TOTAL	

	COAL PULVERIZATION				
				TOTAL HYDROGEN % wt	
48	GRINDABILITY INDEX*		62	DENSITY 68 F ATM. PRESS.	
49	FINENESS % THRU 50 M*		63	Btu PER CU FT	
50	FINENESS % THRU 200 M*		41	Btu PER LB	

64 INPUT-OUTPUT EFFICIENCY OF UNIT % $\frac{\text{ITEM 31} \times 100}{\text{ITEM 29}}$

	HEAT LOSS EFFICIENCY	Btu/lb A. F. FUEL	% of A. F. FUEL
65	HEAT LOSS DUE TO DRY GAS		18.8
66	HEAT LOSS DUE TO MOISTURE IN FUEL		1.2
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2		5.4
68	HEAT LOSS DUE TO COMBUST. IN REFUSE		17.6
69	HEAT LOSS DUE TO RADIATION		1.8
70	UNMEASURED LOSSES		1.5
71	TOTAL		46.3
72	EFFICIENCY = (100 – Item 71)		53.7

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

CALCULATION SHEET

Revised September, 1965

	OWNER OF PLANT TEST NO. BOILER NO. DATE			
20	HEAT [illegible] IN BOILER BLOW-DOWN WATER = LB OF WATER [illegible] PER HR × [ITEM 15 − ITEM 17] / [illegible] = kB/hr			
24	*If impractical to weigh refuse, this item can be estimated as follows* DRY REFUSE PER LB OF AS FIRED FUEL = % ASH IN AS FIRED COAL (24.73) / 100 − % COMB. IN REFUSE SAMPLE [illegible] = .35 CARBON BURNED PER LB AS FIRED FUEL = ITEM 43 47.29 / 100 − [ITEM 22 .35 × ITEM 23 4205 / 14,500] = .371 NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.			
25	DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)}$ × (LB CARBON BURNED PER LB AS FIRED FUEL + $\frac{3}{8}$ S) = $\frac{11 \times \text{ITEM 32 } 6.4 + 8 \times \text{ITEM 33 } 11.0 + 7(\text{ITEM 35 } 82.6 + \text{ITEM 34 } --)}{3 \times (\text{ITEM 32 } 6.4 + \text{ITEM 34 } \ldots)}$ × [ITEM 24 .371 + ITEM 47 .66 / 267] = 14.3			
36	EXCESS AIR† = 100 × $\frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})}$ = 100 × $\frac{\text{ITEM 33 } (11) - \frac{\text{ITEM 34}}{2}}{.2682 (\text{ITEM 35}) (82.6) - (\text{ITEM 33 } (11) - \frac{\text{ITEM 34}}{2})}$ = 98.6 %			
	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	LOSS / HHV × 100 =	LOSS %
65	HEAT LOSS DUE TO DRY GAS = LB DRY GAS PER LB AS FIRED FUEL × C_p × ($t_{lvg} - t_{air}$) = ITEM 25 (14.3) × 0.25 × (ITEM 13) (512) − (ITEM 11) (70) =	1580	65 / 41 × 100 =	18.8
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = ITEM 37 (2.94) / 100 × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) (1294) − (ENTHALPY OF LIQUID AT T ITEM 11) (38)] =	100	66 / 41 × 100 =	1.2
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = 9 × ITEM 44 (4.07) / 100 × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) (1279) − (ENTHALPY OF LIQUID AT T ITEM 11) (38)] =	455	67 / 41 × 100 =	5.4
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = ITEM 22 .35 × ITEM 23 4205 =	1472	68 / 41 × 100 =	17.6
69	HEAT LOSS DUE TO RADIATION* = TOTAL BTU RADIATION LOSS PER HR / LB AS FIRED FUEL × ITEM [illegible]		69 / 41 × 100 =	1.8
70	UNMEASURED LOSSES **		70 / 41 × 100 =	1.5
71	TOTAL			46.3
72	EFFICIENCY = (100 − ITEM 71)			53.7

† For rigorous determination of excess air see Appendix 9.2 — PTC 4.1-1964

* If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may be provided for by assigning a mutually agreed upon value for Item 70.

0:1

SUMMARY SHEET

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

PTC 4.1-a (1964)

	TEST NO	BOILER NO	DATE 5/14/77
OWNER OF PLANT	LOCATION		
TEST CONDUCTED BY	OBJECTIVE OF TEST		DURATION
BOILER MAKE & TYPE		RATED CAPACITY	
STOKER TYPE & SIZE			
PULVERIZER, TYPE & SIZE		BURNER, TYPE & SIZE	
FUEL USED MINE	COUNTY	STATE	SIZE AS FIRED

PRESSURES & TEMPERATURES

1	STEAM PRESSURE IN BOILER DRUM	psia	152
2	STEAM PRESSURE AT S. H. OUTLET	psia	
3	STEAM PRESSURE AT R. H. INLET	psia	
4	STEAM PRESSURE AT R. H. OUTLET	psia	
5	STEAM TEMPERATURE AT S. H. OUTLET	F	
6	STEAM TEMPERATURE AT R. H. INLET	F	
7	STEAM TEMPERATURE AT R. H. OUTLET	F	
8	WATER TEMP. ENTERING (ECON.)(BOILER)	F	226
9	STEAM QUALITY % MOISTURE OR P. P. M.		.95
10	AIR TEMP. AROUND BOILER (AMBIENT)	F	
11	TEMP. AIR FOR COMBUSTION (This is Reference Temperature) †	F	78
12	TEMPERATURE OF FUEL	F	
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F	472
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F	

UNIT QUANTITIES

15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb	
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM	Btu/lb	1195.7
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb	194.2
18	ENTHALPY OF REHEATED STEAM R. H. INLET	Btu/lb	
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb	
20	HEAT ABS/LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb	1001.5
21	HEAT ABS/LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb	
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb	.269
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb	580
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb	.298
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb	6.404

HOURLY QUANTITIES

26	ACTUAL WATER EVAPORATED	lb/hr	11,459
27	REHEAT STEAM FLOW	lb/hr	---
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr	4991
29	TOTAL HEAT INPUT $\frac{\text{(Item 28} \times \text{Item 41)}}{1000}$	kB/hr	5103
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr	25,500
31	TOTAL HEAT OUTPUT $\frac{\text{(Item 26} \times \text{Item 20)} + \text{(Item 27} \times \text{Item 21)} + \text{Item 30}}{1000}$	kB/hr	11,476

FLUE GAS ANAL. (BOILER)(ECON) (AIR HTR) OUTLET

32	CO_2	% VOL	7.3
33	O_2	% VOL	11.5
34	CO	% VOL	—
35	N_2 (BY DIFFERENCE)	% VOL	81.2
36	EXCESS AIR	%	112

FUEL DATA

	COAL AS FIRED PROX. ANALYSIS	% wt		OIL	
37	MOISTURE	16.60	51	FLASH POINT F*	
38	VOL MATTER	48.59	52	Sp. Gravity Deg. API*	
39	FIXED CARBON	8.96	53	VISCOSITY AT SSU* BURNER SSF	
40	ASH	25.85	44	TOTAL HYDROGEN % wt	
	TOTAL		41	Btu per lb	
41	Btu per lb AS FIRED	5103			
42	ASH SOFT TEMP.* ASTM METHOD			GAS	% VOL
	COAL OR OIL AS FIRED ULTIMATE ANALYSIS		54	CO	
43	CARBON	30.90	55	CH_4 METHANE	
44	HYDROGEN	3.76	56	C_2H_2 ACETYLENE	
45	OXYGEN	21.78	57	C_2H_4 ETHYLENE	
46	NITROGEN	.55	58	C_2H_6 ETHANE	
47	SULPHUR	.23	59	H_2S	
40	ASH	25.85	60	CO_2	
37	MOISTURE	16.60	61	H_2 HYDROGEN	
	TOTAL			TOTAL	
	COAL PULVERIZATION			TOTAL HYDROGEN % wt	
48	GRINDABILITY INDEX*		62	DENSITY 68 F ATM. PRESS.	
49	FINENESS % THRU 50 M*		63	Btu PER CU FT	
50	FINENESS % THRU 200 M*		41	Btu PER LB	
64	INPUT-OUTPUT EFFICIENCY OF UNIT %	$\frac{\text{ITEM 31} \times 100}{\text{ITEM 29}}$			

	HEAT LOSS EFFICIENCY	Btu/lb A. F. FUEL	% of A. F. FUEL
65	HEAT LOSS DUE TO DRY GAS		12.4
66	HEAT LOSS DUE TO MOISTURE IN FUEL		3.7
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2		7.5
68	HEAT LOSS DUE TO COMBUST. IN REFUSE		3.1
69	HEAT LOSS DUE TO RADIATION		3.7
70	UNMEASURED LOSSES		1.5
71	TOTAL		31.9
72	EFFICIENCY = (100 – Item 71)		68.1

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

ASME TEST FORM
FOR ABBREVIATED EFFICIENCY TEST

CALATION SHEET

Revised September, 1965

OWNER OF PLANT	TEST NO.	BOILER NO.	DATE

31	HEAT OUTPUT IN BOILER BLOWDOWN WATER = LB OF WATER BLOWDOWN PER HR × $\left[\frac{\text{ITEM 15} - \text{ITEM 17}}{1000}\right]$ = ... LB/hr
24	*If impractical to weigh refuse, this item can be estimated as follows* DRY REFUSE PER LB OF AS FIRED FUEL = $\frac{\overset{25.85}{\%\text{ ASH IN AS FIRED COAL}}}{100 - \%\text{ COMB. IN REFUSE SAMPLE}}$ .269 CARBON BURNED PER LB AS FIRED FUEL = $\frac{\overset{\text{ITEM 43}}{30.90}}{100} - \left[\frac{\overset{\text{ITEM 22}}{.269} \times \overset{\text{ITEM 23}}{580}}{14{,}500}\right] = .298$ NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.
25	DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)} \times (\text{LB CARBON BURNED PER LB AS FIRED FUEL} + \frac{3}{8}S)$ $= \frac{11 \times \overset{\text{ITEM 32}}{7.3} + 8 \times \overset{\text{ITEM 33}}{11.5} + 7\left(\overset{\text{ITEM 35}}{81} + \overset{\text{ITEM 34}}{--}\right)}{3 \times \left(\overset{\text{ITEM 32}}{11.5} + \overset{\text{ITEM 34}}{--}\right)} \times \left[\overset{\text{ITEM 24}}{.298} + \frac{\overset{\text{ITEM 47}}{.23}}{267}\right] = 6.404$
36	EXCESS AIR† $= 100 \times \frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})} = 100 \times \frac{\overset{\text{ITEM 33}}{11.5} - \frac{\text{ITEM 34}}{2}}{.2682(\underset{81.2}{\text{ITEM 35}}) - (\underset{11.5}{\text{ITEM 33}} - \frac{\text{ITEM 34}}{2})} = 112\%$

	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	$\frac{\text{LOSS}}{\text{HHV}} \times 100 =$	LOSS %
65	HEAT LOSS DUE TO DRY GAS = $\frac{\text{LB DRY GAS}}{\text{PER LB AS FIRED FUEL}}$ $\times C_p \times (t_{lvg} - t_{air})$ Unit = $\overset{\text{ITEM 25}}{6.404} \times 0.25 \times \overset{(\text{ITEM 13})}{472} - \overset{(\text{ITEM 11})}{78}$ = ...	631	$\frac{65}{41} \times 100 =$	12.4
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $\frac{\overset{16.6}{\text{ITEM 37}}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) 1178.9 − (ENTHALPY OF LIQUID AT T ITEM 11)] 46 = ...	188	$\frac{66}{41} \times 100 =$	3.7
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = 9 × $\frac{\overset{3.76}{\text{ITEM 44}}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) 1178.9 − (ENTHALPY OF LIQUID AT T ITEM 11)] 48 = ...	383	$\frac{67}{41} \times 100 =$	7.5
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = $\overset{\text{ITEM 22}}{.269} \times \overset{\text{ITEM 23}}{580}$ = ...	156	$\frac{68}{41} \times 100 =$	3.1
69	HEAT LOSS DUE TO RADIATION* = $\frac{\text{TOTAL BTU RADIATION LOSS PER HR}}{\text{LB AS FIRED FUEL}}$ ITEM [illegible]	......	$\frac{69}{41} \times 100 =$	3.7
70	UNMEASURED LOSSES **	......	$\frac{70}{41} \times 100 =$	1.5
71	TOTAL	......	......	31.9
72	EFFICIENCY = (100 − ITEM 71)	......	......	68.1

† For rigorous determination of excess air see Appendix 9.2 – PTC 4.1-1964

* If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may by provided for by assigning a mutually agreed upon value for Item 70.

BOILER NO. 1
ERIE CITY IRON WORKS
Erie, Pennsylvania

FOR MARYLAND INSTITUTION FOR MEN
BREATHEDSVILLE, MARYLAND

October 1, 1963
G.O. 96/63

Predicted Performance Only
Guaranteed efficiency at 60,000 lb/steam/hour is 75.0%

	Percent of load				
	17	33	67	1.0	Peak
1. Evaporation, actual, pounds per hour	13,083	26,167	52,333	78,500	85,000
2. Pressure in the drum, psig	175	175	175	175	175
3. Feedwater temperature °F	220	220	220	220	220
4. Temperature of flue gases leaving the furnace °F				1,885	
5. Temperature of flue gases leaving the boiler °F	422	450	513	580	597
6. Excess air at boiler outlet % (See note below)	96.45	57.11	40.5	34.0	31.3
7. Temperature of air at windbox °F	80	80	80	80	80
8. Dust collector draft loss, in H_2O (See below)	0.20	0.40	1.03	2.55	3.00
9. Gas dust and damper draft loss (See note below)	0.10	0.10	0.20	0.45	0.55
10. Furnace and boiler draft loss	0.20	0.33	0.53	0.95	1.10
11. Total draft required inches H_2O	0.50	0.83	1.76	3.95	4.65
12. Induced draft design static			See Fan Design Below		
13. Stoker and windbox air resistance (See note below)	0.11	0.32	0.70	1.40	1.60
14. Duct and Damper air resistance (No orifice in duct)	0.10	0.10	0.20	0.45	0.55
15. Total air resistance inches H_2O	0.21	0.42	0.90	1.85	2.15
16. Forced draft fan static design			See Fan Design Below		
17. Flue gas leaving the boiler, lb/hr	25,837	40,121	72,084	104,693	111,535
18. Air required for combustion, lb/hr	24,080	36,748	65,349	94,464	100,435
19. Fuel burned, lb/hr	1,274	2,447	4,885	7,420	8,052
20. Furnace heat liberation Btu/cu ft	4,320	8,300	16,550	25,800	28,000
21. Heat release Btu/sq ft active grate (at 129 sq ft grate)	93,600	181,000	358,000	543,000	589,000
22. Moisture in steam leaving the boiler %	1/2 of 1	1/2 of 1	1/2 of 1	1/2 of 1	1/2 of 1
23. Unit efficiency %	77.71	80.76	80.43	78.91	78.53
24. Losses:					
A. Dry gas %	12.34	10.73	11.27	12.43	12.61
B. Moisture in fuel and hydrogen %	4.02	4.07	4.17	4.28	4.31
C. Moisture in air %	0.33	0.29	0.30	0.33	0.34
D. Unburned combustible % (See note	0.80	1.00	1.50	2.00	2.20
below*)	0.80	1.00	1.50	2.00	2.20
E. Radiation %	3.30	1.65	0.83	0.55	0.51
F. Unaccounted for %	1.50	1.50	1.50	1.50	1.50
G. Total %	22.29	19.24	19.57	21.09	21.47

NOTE: Items 8 and 9 are per Aerotec Industries, Inc. performance dated July 22, 1963. Items 6 13 and 24-D are per Hoffman Comb. Engineering Company performance dated June 12, 1963.

*See Item 24-D above

The unburned combustible loss is as given by Hoffman Comb. Engr. Company based on reinjection from boiler hoppers and decantation collector. Guaranteed overall boiler and stoker efficiency is 75.0% at 60,000 pounds of steam per hour.

BOILER NO. 2
ERIE CITY IRON WORKS
Erie, Pennsylvania

FOR MARYLAND INSTITUTION FOR MEN
BREATHEDSVILLE, MARYLAND

October 1, 1963
G.O. 97/63

Predicted Performance Only
Guaranteed efficiency at 60,000 lb/steam/hour is 75.0%

	Percent of load				
	17	33	67	1.0	Peak
1. Evaporation, actual pounds per hour	10,000	20,000	40,000	60,000	66,000
2. Pressure in the drum, psig	175	175	175	175	175
3. Feedwater temperature °F	220	220	220	220	220
4. Temperature of flue gases leaving the furnace °F				1,870	
5. Temperature of flue gases leaving the boiler °F	432	454	519	590	611
6. Excess air at boiler outlet % (See note below)	96.45	57.11	40.5	34.0	31.3
7. Temperature of air at windbox °F	80	80	80	80	80
8. Dust collector draft loss, in H_2O (See below)	0.20	0.40	1.00	2.40	3.00
9. Gas dust and damper draft loss (See note below)	0.10	0.10	0.20	0.45	0.55
10. Furnace and boiler draft loss	0.20	0.35	0.56	1.05	1.25
11. Total draft required inches H_2O	0.50	0.85	1.76	3.90	4.80
12. Induced draft design static		See fan design below			
13. Stoker and windbox air resistance (See note below)	0.11	0.32	0.70	1.40	1.60
14. Duct and Damper air resistance (No orifice in duct)	0.10	0.10	0.20	0.45	0.55
15. Total air resistance inches H_2O	0.21	0.42	0.90	1.85	2.15
16. Forced draft fan static design		See fan design below			
17. Flue gas leaving the boiler, lb/hr	19,854	30,792	55,277	80,340	87,073
18. Air required for combustion, lb/hr	18,504	28,203	50,112	72,490	78,407
19. Fuel burned, lb/hr	979	1,878	3,746	5,694	6,286
20. Furnace heat liberation Btu/cu ft	4,620	8,850	17,700	26,900	29,600
21. Heat release Btu/sq ft active grate (at 129 sq ft grate)	100,000	192,000	383,000	583,000	642,000
22. Moisture in steam leaving the boiler%	1/2 of 1	1/2 of 1	1/2 of 1	1/2 of 1	1/2 of 1
23. Unit efficiency %	77.07	80.46	80.15	78.58	78.09
24. Losses:					
A. Dry gas %	12.41	10.85	11.45	12.67	12.97
B. Moisture in fuel and hydrogen%	4.02	4.07	4.18	4.30	4.34
C. Moisture in air %	0.34	0.29	0.31	0.34	0.35
D. Unburned combustible% (See note below*)	0.80	1.00	1.50	2.00	2.20
E. Radiation %	3.66	1.83	0.91	0.61	0.55
F. Unaccounted for %	1.50	1.50	1.50	1.50	1.50
G. Total %	22.93	19.54	19.85	21.42	21.91

NOTE: Items 8 and 9 are per Aerotec Industries, Inc. performance dated July 22, 1963.
Items 6, 13 and 24-D are per Hoffman Comb. Engineering Company performance dated June 12, 1963.

*See Item 24-D above
The unburned combustible loss is as given by Hoffman Comb. Engr. Company based on reinjection from boiler hoppers and decantation collector. Guaranteed overall boiler and stoker efficiency is 75.0% at 60,000 pounds of steam per hour.

APPENDIX C

PROCEDURE FOR ESTIMATING STACK VELOCITY

The emissions were monitored at the stack using isokinetic sampling techniques. Achieving isokinetic sampling at MCI was greatly complicated by the fact that the stack is sized for all three boilers firing simultaneously at full load. Only one boiler is operated at a time at approximately one-half load. As a result, the average stack gas velocity is too low to be read on an S-type pitot tube. Because of the dirty nature of the stack gas, use of a hot wire anemometer or similar device capable of reading the low flow is not practical. As an alternative approach, the stack gas velocity was computed on the basis of the boiler load, the experimentally determined boiler efficiency, the fuel characteristics, and the Orsat analysis at the stack. This procedure is an extension of standard boiler monitoring techniques. The calculation used to compute stack gas velocity is as follows:

(1) The fraction of nitrogen in the flue gas is determined from the Orsat analysis (which condenses all the water prior to analysis) by recognizing that:

$$N_2 = 100 - CO_2 - O_2 - CO \qquad \text{(C-1)}$$

(2) The weight of nitrogen and carbon per mole of dry flue gas is then computed by Equations (C-2) and (C-3).

$$\text{lb}_{N_2}/\text{mole DFG} = \frac{N_2}{100} \times 28 \qquad \text{(C-2)}$$

$$\text{lb}_C/\text{mole DFG} = \frac{CO + CO_2}{100} \times 12 \qquad \text{(C-3)}$$

(3) The nitrogen-to-carbon ratio in the flue gas is computed as the ratio of the nitrogen and carbon levels in the dry flue gas.

$$\frac{\text{lb}_{N_2}}{\text{lb}_C} = \frac{\text{Equation (C-2)}}{\text{Equation (C-3)}} \qquad \text{(C-4)}$$

(4) The nitrogen-to-carbon ratio in the flue gas is then multiplied by the carbon-to-fuel ratio computed by Equation (C-5) and the air-to-nitrogen ratio to determine the air-to-fuel ratio.

$$\frac{lb_C}{lb_{fuel}} = \frac{m\rho_c}{m\rho_c+n\rho_d}(\%C_c) + \frac{n\rho_d}{m\rho_c+n\rho_d}(\%C_d) \qquad \text{(C-5)}$$

where m is the volume fraction coal and n is the volume fraction dRDF; %C and ρ are the as-received carbon content and the bulk density of the respective fuels c(coal) and d(dRDF).

$$\frac{lb_{air}}{lb_{fuel}} = \left(\frac{lb_{N_2}}{lb_C}\right)\left(\frac{lb_C}{lb_{fuel}}\right)\left(\frac{lb_{air}}{lb_{N_2}}\right) \qquad \text{(C-6)}$$

Note: $\frac{lb\ air}{lb\ N_2}$ is the constant 1.30

(5) The wet flue gas is then determined by recognizing that the total amount of flue gas must be equal to the fraction of the input fuel burned plus the pounds of air added to the fuel.

$$\frac{lb\ of\ WFG}{lb\ of\ fuel} = \left(\frac{lb_{fuel}}{lb_{fuel}} - \frac{lb_{ash}}{lb_{fuel}}\right) + \frac{lb_{air}}{lb_{fuel}} \qquad \text{(C-7)}$$

(6) The wet flue gas is then converted into a volumetric flux by multiplying by the standard flue gas density corrected to stack conditions. Note that the actual density could be computed, but the error introduced by assuming standard combustion products is of a lower order than the sampling error of the composition of the fuel submitted to the laboratory for ultimate analyses.

$$\frac{cu\ ft\ of\ WFG\ @\ T_s}{lb\ of\ fuel} = \frac{WFG}{0.071}\ \frac{460+T_s}{560} \qquad \text{(C-8)}$$

Note: .071 is assumed to be the density of flue gas at 560°R, and T_s is the stack temperature in °F.

This result is then converted into an average gas velocity by recognizing that the gas flux will be the cubic feet of gas per pound of fuel burned multiplied by the rate of fuel consumption in the boiler with this product then divided by the cross-sectional area of the stack. These relationships [expressed in Equation (C9)] assume that the velocity flux is to be computed over the same heat balance period as the boiler efficiency test. The ratio of pounds of blend divided by run time can be replaced by the amount of fuel needed to produce the steam generation rate (as read off the strip chart recorder) once the boiler efficiency is known for a given excess air level.

$$U = \frac{\text{(cu ft of WFG/lb fuel) (lb fuel/sec)}}{\frac{\pi}{4}\ D^2} = \text{ft/sec} \qquad \text{(C-9)}$$

where D is the stack diameter, and U is the gas velocity.

(7) The calculated gas velocity can be readily converted into a velocity head (feet of air) by employing a rearrangement of Bernoulli's equation:

$$\Delta h = \frac{\rho U^2}{2g\ (\rho_m - \rho)} \qquad \text{(C-10)}$$

where ρ is the gas density under stack conditions (lb/cu ft), ρ_m is the density of the manometer fluid (lb/cu ft), and g is the gravitational constant (ft/sec^2).

Equation (C-10) is the velocity head as would be measured by a standard pitot tube. As a result, this Δh needs to be multiplied by a correction factor (≈ 0.91) which relates standard pitot tube results to the measurements of an S-type pitot probe and by a constant to convert from feet of air head to inches of water. This calculated apparent stack velocity is then used to calculate an isokenetic flue gas sampling rate.

APPENDIX D
CASCADE IMPACTOR DATA

TABLE D-1. DECEMBER CASCADE IMPACTOR RAW DATA

DECEMBER

	Total Flow (CF)	Elapsed Time (Min)	Impactor Flow Rate (CFM)	Assumed Part Density (g/cc)	Impactor Temp. (°F)	Stack Temp. (°F)		1	2	3	4	5	6	7	Filter
1:0-1	14.47	30	2.6	1.0	345	345	D_{50}	16	7.7	2.8	1.3	.7	0	--	
Date: 12/6/77							mg	0	0	9.6	7.1	48.0	84.46	0	11.9
							CUM %	0	0	12.53	21.80	84.46	--	84.46	100
1:0-2	41.02	60	2.6	1.0	345	345	D_{50}	16	7.7	2.8	1.3	.7	.3	--	
Date: 12/6/77							mg	0	4.2	9.3	7.9	12.8	8.1	0.4	15.8
							CUM %	0	7.18	23.08	36.58	58.46	72.31	72.99	100
1:0-3	15.91	30	.57	1.0	370	370	D_{50}	34	17	5.7	2.7	1.5	.6	.4	
Date: 12/10/77							mg	11.9	7.9	8.1	12.2	2.9	8.5	11.9	19.0
							CUM %	14.44	24.03	33.86	48.67	52.18	62.50	76.94	100
1:1-1	34.36	30	.58	1.0	390	390	D_{50}	31.0	16.0	5.7	2.7	1.9	.7	.4	
Date: 12/8/76							mg	0	4.6	40.0	30.1	0.3	22.2	13.5	27.3
							CUM %	0	3.33	32.32	54.13	54.35	70.43	80.22	100
1:1-2	28.26	30	.59	1.0	390	390	D_{50}	31.0	16.0	5.7	2.7	1.4	.7	.4	
Date: 12/13/76							mg	7.0	4.7	31.4	32.3	15.7	40.6	1.7	35.8
							CUM %	4.14	6.91	25.47	44.56	53.84	77.84	78.84	
1:1-3	30.77	30	.59	1.0	380	380	D_{50}	31	16	5.7	2.7	1.4	.7	.4	
Date: 12/13/76							mg	0	12.6	34.8	22.5	16.2	3.3	22/6	15.6
							CUM %	0	9.87	37.15	54.78	67.48	70.06	87.77	100

TABLE D-2. JANUARY CASCADE IMPACTOR RAW DATA

JANUARY	Total Flow (CF)	Elapsed Time (Min)	Impactor Flow Rate (CFM)	Assumed Part Density (g/cc)	Impactor Temp. (°F)	Stack Temp. (°F)		1	2	3	4	5	6	7	Filter
1:0-1 Date: 1/20/77	19.92	30	.763	1.0	390	390	D_{50}	30	13.5	4.9	2.25	1.25	.56	.35	
							mg	2.0	6.4	28.3	33.7	3.4	0	0	4.8
							CUM %	2.54	10.69	46.69	89.57	93.89	93.89	93.89	100
1:0-2 Date: 1/21/77	19.1	30	.610	1.0	375	375	D_{50}	31	15	5.6	2.55	1.45	.65	.42	
							mg	0	4.9	11.1	19.9	3.2	0	0	0.5
							CUM %	0	12.37	40.40	90.66	98.74	98.74	98.74	100
1:0-3 Date: 1/21/77	22.53	30	.54	1.0	375	375	D_{50}	33	16	5.9	2.7	1.53	.69	.44	
							mg	0	3.7	15.1	9.0	13.0	4.5	0	11.8
							CUM %	0	6.48	32.92	48.69	71.45	79.33	79.33	100
1:0-5 Date: 1/24/77	13.95	30	.443	1.0	400	400	D_{50}	37	18	6.5	3.0	1.7	.77	.51	
							mg	0	0	6.1	15.6	5.2	2.4	0	7.6
							CUM %	0	0	16.53	58.81	72.90	79.40	79.40	100

TABLE D-3. MARCH CASCADE IMPACTOR RAW DATA

MARCH	Total Flow (CF)	Elapsed Time (Min)	Impactor Flow Rate (CFM)	Assumed Part Density (g/cc)	Impactor Temp. (°F)	Stack Temp. (°F)		1	2	3	4	5	6	7	Filter
1:0-1 Date: 3/19/77	11.33	30	.61	1.0	390	390	D_{50}	31	15	5.5	2.5	1.4	.64	.41	
							mg	0.9	3.9	20.7	15.4	9.5	3.8	1.5	7.4
							CUM %	1.43	7.61	40.41	64.82	79.87	85.90	88.27	100
1:0-2 Date: 3/19/77	7.16	20	.58	1.0	390	390	D_{50}	32	15.5	5.7	2.7	1.45	.67	.34	
							mg	13.1	3.7	11.9	9.9	5.4	2.6	0.7	4.9
							CUM %	25.10	32.18	54.98	73.95	84.29	89.27	90.61	100
1:0-3 Date: 3/21/77	10.44	30	.58	1.0	415	415	D_{50}	32	15.5	5.7	2.7	1.45	.67	.43	
							mg	0.9	1.8	19.5	15.7	8.4	2.2	1.6	11.8
							CUM %	1.45	4.36	35.86	61.23	74.80	78.35	80.94	100
1:0-4 Date: 3/21/77	8.13	20	.67	1.0	415	415	D_{50}	29.5	14.5	5.3	2.5	1.4	.61	.40	
							mg	1.0	1.3	17.3	9.9	7.1	3.1	5.8	6.1
							CUM %	1.94	4.46	37.98	57.17	70.93	76.94	88.18	100
1:0-5 Date: 3/22/77	7.62	20	.62	1.0	370	370	D_{50}	31	15	5.4	2.4	1.3	.64	.42	
							mg	1.6	2.9	12.7	9.2	4.7	1.9	0.8	4.5
							CUM %	4.18	11.75	44.91	68.93	81.20	86.16	88.25	100
1:0-6 Date: 3/28/77	10.29	30	.54	1.0	370	370	D_{50}	33	16.5	5.9	2.8	1.55	.70	.45	
							mg	3.6	2.9	18.4	11.2	8.9	4.2	2.6	8.1
							CUM %	6.01	10.85	41.57	60.27	75.13	82.14	86.48	100
1:0-7 Date: 3/31/77	7.01	20	.54	1.0	360	360	D_{50}	33	16.5	5.9	2.8	1.55	.70	.45	
							mg	2.3	4.3	5.4	6.5	14.3	2.2	1.9	7.5
							CUM %	5.18	14.86	27.03	41.67	73.87	78.83	83.11	100
1:0-8 Date: 4/1/77	5.54	15	.60	1.0	390	390	D_{50}	31	15	5.6	2.55	1.40	.66	.42	
							mg	1.2	2.5	12.6	8.1	6.3	2.1	1.1	6.1
							CUM %	3.00	9.25	40.75	61.00	76.75	82.00	84.75	100
1:0-9 Date: 4/1/77	5.22	15	.55	1.0	390	390	D_{50}	33	16	5.8	2.75	1.50	.69	.44	5.5
							mg	0.8	1.6	9.8	7.5	6.0	2.6	0.6	100
							CUM	2.33	6.98	35.47	57.27	74.71	82.27	84.01	

(continued)

TABLE D-3. (continued)

MARCH	Total Flow (CF)	Elapsed Time (Min)	Impactor Flow Rate (CFM)	Assumed Part. Density (g/cc)	Impactor Temp. (°F)	Stack Temp (°F)		1	2	3	4	5	6	7	Filter
1:1-1 Date: 3/23/77	11.18	30	.62	1.0	385	385	D_{50}	31	15	5.4	2.5	1.30	.65	.43	
							mg	0.3	1.5	15.4	10.4	4.4	2.8	4.6	4.6
							CUM %	0.68	4.09	39.09	62.73	72.73	79.09	89.55	100
1:1-2 Date: 3/23/77	8.76	30	.45	1.0	400	400	D_{50}	37	18	6.7	3.0	1.70	.77	.50	
							mg	0.2	1.1	8.9	9.1	4.6	2.4	4.4	14.7
							CUM %	0.44	2.86	22.47	42.51	52.64	57.93	67.62	100
1:1-3 Date: 3/24/77	12.43	30	.68	1.0	390	390	D_{50}	31	16	5.6	2.5	1.30	.65	.42	
							mg	4.7	2.2	13.9	9.4	3.5	1.1	11.3	22.1
							CUM %	6.89	10.12	30.50	44.28	49.41	51.03	67.60	100
1:1-1 Date: 3/29/77	8.54	25	.53	1.0	380	380	D_{50}	33	16.5	5.9	2.75	1.55	.70	.45	
							mg	0.9	0.9	8.9	7.7	2.6	3.9	7.2	16.0
							CUM %	1.87	3.74	22.25	38.25	43.66	51.77	66.74	100
1:1-2 Date: 3/29/77	6.77	20	.51	1.0	390	390	D_{50}	34	17	6.0	2.75	1.60	.70	.47	
							mg	0.2	0.7	10.1	7.5	3.6	2.9	3.8	12.7
							CUM %	0.48	2.18	26.48	44.58	53.28	60.28	69.48	100
1:2-3 Date: 3/30/77	6.3	20	.48	1.0	380	380	D_{50}	35	17.5	6.4	2.7	1.60	.74	.49	11.4
							mg	1.3	1.6	8.1	7.5	5.6	1.3	1.5	100
							CUM %	3.39	7.5	28.72	48.30	62.92	66.32	70.23	
BLANK Date: 3/16/77	10.71	30	.60	1.0	400	400	D_{50}								
							mg	0.6	0.1	0.5	0.3	0.7	0.7	0.3	3.1
							CUM %								

TABLE D-4. MAY CASCADE IMPACTOR RAW DATA

MAY	Total Flow (CF)	Elapsed Time (Min)	Impactor Flow Rate (CFM)	Assumed Part. Density (g/cc)	Impactor Temp. (°F)	Stack Temp. (°F)		1	2	3	4	5	6	7	Filter
1:0-1 Date: 5/3/77	10.84	30	.56	1.0	360	360	D_{50}	32.0	15.5	5.80	2.60	1.50	0.69	0.47	0.47
							mg	0.7	1.8	17.4	14.7	9.6	3.9	2.9	8.9
							CUM %	1.17	1.17	33.22	57.76	73.79	80.30	85.14	100
1:0-2 Date: 5/4/77	7.18	20	.57	1.0	360	360	D_{50}	32.0	15.5	5.80	2.60	1.50	0.69	0.47	
							mg	0.7	1.1	9.6	7.5	4.1	3.5	3.1	9.7
							CUM %	1.78	4.58	29.01	48.09	58.53	67.43	75.32	100
1:0-3 Date: 5/5/77	5.3	15	.62	1.0	420	420	D_{50}	31	15	5.5	2.5	1.4	.62	.40	
							mg	0.8	1.2	14.3	14.0	10.0	6.4	1.7	6.0
							CUM %	1.47	3.68	29.96	55.70	74.08	85.84	88.97	100
1:0-4 Date: 5/5/77	6.84	20	.56	1.0	400	400	D_{50}	32	15.5	5.8	2.6	1.5	.69	.47	
							mg	0.9	0.8	11.9	12.9	7.4	1.9	1.5	6.2
							CUM %	2.07	3.91	31.26	60.92	77.93	82.30	85.75	100
1:0-5 Date: 5/16/77	3.6	10	.60	1.0	380	380	D_{50}	31	15.5	5.7	2.6	1.45	.65	.42	
							mg	0.2	0.6	1.4	4.4	3.2	3.5	1.6	0.8
							CUM %	1.27	5.10	14.01	42.04	62.42	84.71	94.90	100
1:0-6 Date: 5/16/77	7.03	15	.80	1.0	435	435	D_{50}	27	13	4.8	2.2	1.2	.54	.35	
							mg	0.0	1.7	25.7	12.9	4.1	3.0	3.3	7.1
							CUM %	0	2.94	47.40	69.72	76.82	82.01	87.72	100
BLANK 1-0 Date: 5/4/77	4.46	15	.45	1.0	360	360	D_{50}								
							mg	0.3	0.4	1.0	0.5	0.5	0	0.2	0.3
							CUM %								
1:1-1 Date: 5/12/77	8.96	20	.77	1.0	415	415	D_{50}	28	14	4.9	2.2	1.2	.55	.35	
							mg	0.6	1.8	16.8	10.5	4.1	2.7	3.6	10.2
							CUM %	1.19	4.77	38.17	59.05	67.20	72.56	79.72	100
1:1-2 Date: 5/12/77	7.95	20	.66	1.0	400	400	D_{50}	30	10.4	5.4	2.4	1.35	.60	.39	
							mg	0.2	1.3	12.3	9.9	4.7	2.7	2.0	9.1
							CUM %	0.47	3.55	32.70	56.16	67.30	73.70	78.44	100
1:1-3 Date: 5/13/77	6.36	15	.70	1.0	400	400	D_{50}	29	14	5.2	2.3	1.3	.50	.37	
							mg	0.0	2.0	9.9	7.4	1.8	1.3	2.5	7.7
							CUM %	0	6.13	36.50	59.20	64.72	68.71	76.38	100

(continued)

TABLE D-4. (continued)

MAY	Total Flow (CF)	Elapsed Time (Min)	Impactor Flow Rate (CFM)	Assumed Part. Density (g/cc)	Impactor Temp. (°F)	Stack Temp. (°F)		1	2	3	4	5	6	7	Filter
BLANK 1-1 Date: 5/13/77	6.29	15	.69	1.0	400	400	D								
							mg	0.4	0.1	0.6	0.6	1.3	0.7	0.6	0.7
							CUM %								
1:2-1 Date: 5/10/77	7.33	20	.63	1.0	420	420	D	30	15	5.4	2.5	1.4	.62	.4	
							mg	0.8	1.6	11.6	8.9	3.1	2.8	6.1	14.2
							CUM %	1.63	4.89	28.51	46.64	52.95	58.66	71.08	100
1:2-2 Date 5/10/77	7.34	30	.63	1.0	425	425	D	30	15	5.4	2.5	1.4	.62	.4	
							mg	1.2	1.2	2.4	12.2	16.5	1.2	2.1	11.0
							CUM %	2.51	5.02	10.04	35.56	70.08	72.59	76.99	100
1:2-3 Date: 5/11/77	8.68	20	.73	1.0	410	410	D	28	14	5	2.3	1.3	.57	.37	
							mg	1.2	1.7	20.1	13.3	5.0	2.4	3.2	12.7
							CUM %	2.01	4.87	38.59	60.91	69.30	73.32	78.69	100
BLANK 1-2 Date: 5/11/77	8.53	20	.72	1.0	420	420	D								
							mg	0.5	0.3	1.1	1.1	0.8	0.7	0.5	0
							CUM %								
0:1-1 Date: 5/14/77	8.0	20	.66	1.0	380	380	D	29	14.5	5.2	2.4	1.3	.62	.39	
							mg	0.0	0.5	0.0	7.5	2.4	1.7	7.1	23.6
							CUM %	0	1.17	1.17	18.69	24.30	28.27	44.86	100
0:1-2 Date: 5/14/77	11.9	30	.65	1.0	390	390	D	29	14.5	5.2	2.4	1.3	.62	.39	
							mg	0.4	1.8	18.9	13.8	3.9	4.2	13.0	32.4
							CUM %	0.45	2.49	23.87	39.48	43.89	48.64	63.35	100

APPENDIX E

DISCUSSION OF MONSANTO'S ESP TEST DATA

SYSTECH analyzed Monsanto's ESP test data to determine how the fly ash from coal-only and 1:1 and 1:2 blend tests affected the precipitator performance. Figure E-1 plots the results of this analysis with inverse penetration as a function of the specific collector area, the applied voltage, and the square root of the current. These parameters were chosen as axes because the Deutch Equation (E-1) indicates that these axes should yield a straight line on semilog paper as demonstrated in the following.

$$\eta = 1 - P = 1 - e^{-(A/Q)W} \qquad \text{(E-1)}$$

where η = probability of particle capture
P = penetration
A = collector electrode area ft^2
Q = gas glow CFM
W = migration velocity

Further reduction of Equation (E-1) yields the following:

$$\ln P = -\frac{AW}{Q} \qquad \text{(E-2)}$$

and

$$\ln \frac{1}{P} = \frac{AW}{Q} \qquad \text{(E-3)}$$

The migration velocity is a function of electric field strength (E_p) and particle charge (q).

$$W \,\alpha\, q\, E_p \qquad \text{(E-4)}$$

For a uniform field, the field strength (E_p) is the applied voltage (V) to the collector electrodes divided by the gap between the electrodes. Also, the charge per particle (q) is a function of the electron cloud density which is proportional to the square root of the current flow (i) for collision

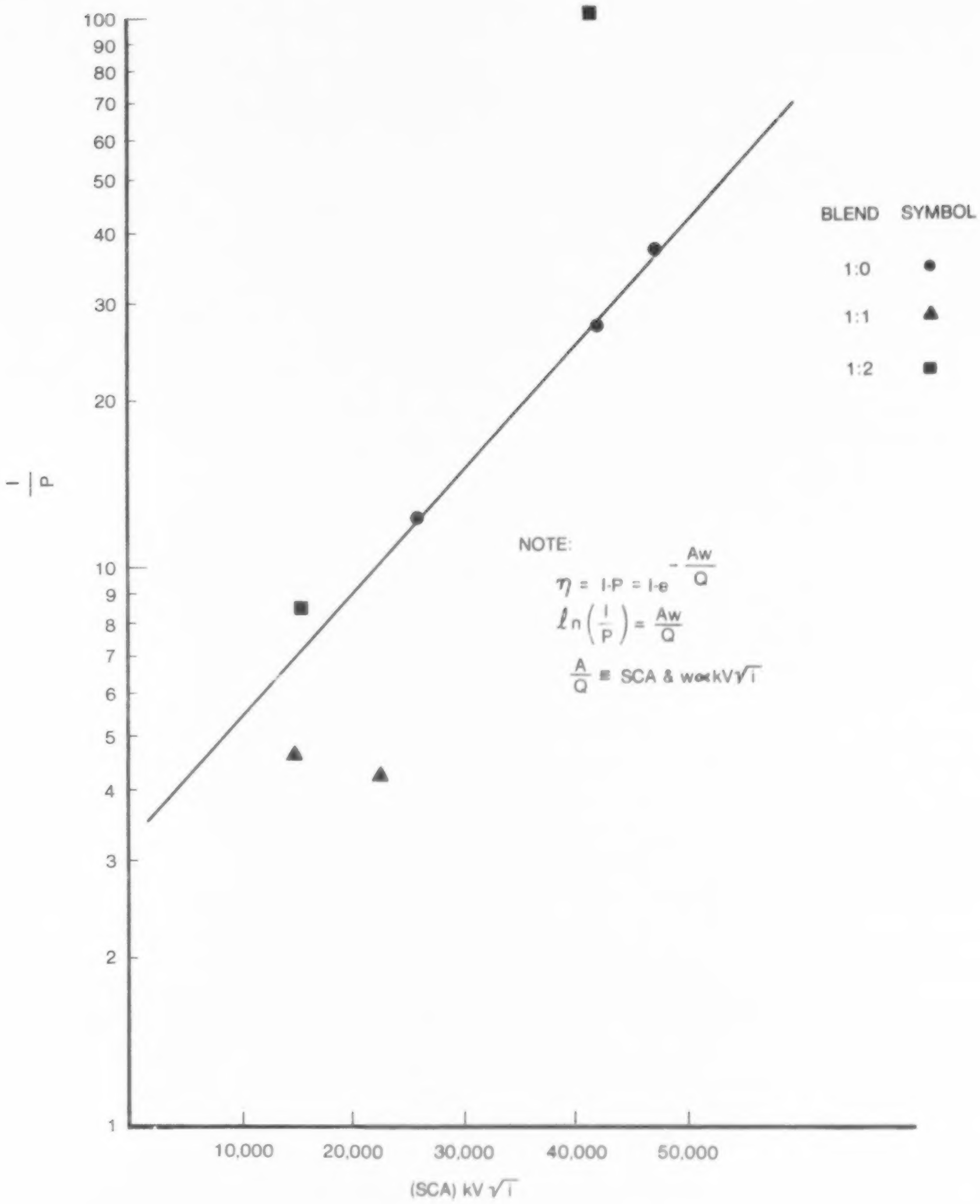

Figure E-1. Precipitability of blend fly ash component to coal-only conditions.

charging. Therefore, substituting these relationships into Equation (E-4) yields the following equation:

$$W \alpha V \sqrt{i} \qquad \text{(E-5)}$$

Since A/Q is commonly referred to as SCA, Equation (E-3) can now be expressed as:

$$\ln \frac{1}{P} \alpha \text{ SCA } V\sqrt{i} \qquad \text{(E-6)}$$

Table E-1 summarizes all of the Monsanto data, and Figure E-1 presents a logarithmic plot of 1/P versus SCA for the various blends. If the precipitator performs normally, regardless of the variation in these parameters, the results should plot as a straight line.

However, the coal-only ash had resistivities too low for proper precipitation. The 1:1 and the 1:2 ash were slightly less and slightly more precipitable, respectively, than the coal-only ash.

The difference between the resistivity for the first 1:2 test data and the resistivity for the rest of the data is probably real. After the coal-only runs were completed, the precipitator was thoroughly cleaned. Consequently, most of the power applied to the cells for this first 1:2 test probably passed through the air gap. During the 1:1 test, cell after cell was taken off line because of the short-circuiting over the dielectric bridge. Consequently, while the applied voltage or field was correct, a significant amount of current probably leaked through the insulating hangers to the grounded electrodes. If it is assumed that half of the current bypassed the air gap, then the aerosol data for the 1:1 test aligns with the aerosol data for the 1:2 test. The collection data for the 1:1 test, therefore, has questionable validity.

Because the first 1:2 run had more fly ash precipitation than the coal-only run, it is likely that substituting dRDF for coal will not seriously degrade the precipitator performance. This conclusion, however, must be verified by further testing.

TABLE E-1. FIELD PORTABLE ELECTROSTATIC PRECIPITATOR DATA

DATE	FLOW (ACFM)	SCA (Ft.^{2}/KCFM)	Temp. (°F)	AVERAGE ELEC. COND.			INLET COND. (gr/SCF) MEAS.		OUTLET COND. MEASURED (gr/SCF)	EFFICIENCY (%)
				CELL	VOLT (KV)	C.D. (UA/Ft.^{2})				
5/5/77	1500	320	480	1	27	15		0.16	0.0012	99.25
				2	34	30				
1:0				3	32	22		0.19	0.0082	95.7
coal				4	32	16				
only				5	32	30	Avg.	0.175	0.0047	97.3
				1						
				2						
				3						
				4						
				5						
5/10/77	1500	320	470	1	32	4		0.251	0.0040	98.4
				2	36	12		0.		
1:2				3	34	15		0.201	0.00047	99.8
Blend				4	32	10				
				5	36	42	Avg.	0.226	0.00226	99.0
				1						
				2						
				3						
				4						
				5						

(continued)

TABLE E-1. (continued)

DATE	FLOW (ACFM)	SCA (Ft.^{2}/KCFM)	Temp. (°F)	AVERAGE ELEC. COND. CELL	VOLT (KV)	C.D. (UA/Ft.^{2})	INLET COND. (gr/SCF) MEAS.		OUTLET COND. MEASURED (gr/SCF)	EFFICIENCY (%)
5/11	3000	160	530	1	32	5		0.15	.0178	88.1
1:2				2	37	7		0.098	.0114	88.3
Blend				3	30	0.8				
				4	38	12				
				5	37	17	AVG.	0.124	0.0146	88.2
				1						
				2						
				3						
				4						
				5						
5/12	1500	320	470	1	23	10		0.20	0.059	70.6
				2	25	15				
1:1				3	24	9		0.18	0.030	83.3
Blend				4	30	8				
				5	32	15	AVG.	0.19	0.0445	76.6
				1						
				2						
				3						
				4						
				5						

(continued)

TABLE E-1. (continued)

DATE	FLOW (ACFM)	SCA (Ft.^{2}/KCFM)	Temp. (°F)	AVERAGE ELEC. COND.			INLET COND.		OUTLET COND. MEASURED (gr/SCF)	EFFICIENCY (%)
				CELL	VOLT (KV)	C.D. (UA/Ft.^{2})	(gr/SCF)	MEAS.		
5/13	3000	160	500	1	24	12		0.12	0.0425	64.6
				2	25	10		0.23	0.0331	85.6
1:1				3	22	8				
Blend				4	23	8				
				5	42	20	AVG.	0.175	0.0378	78.4
				1						
				2						
				3						
				4						
				5						
5/16	1200	320	450	1	27	10		0.164	0.00605	96.3
				2	33	20				
(Note:	Operating	4 cells)		3	33	28				
1:0 coal				4	28	18				
only				5	--	--				
5/16	1200	240	450	1	26	11		0.127	0.0103	91.9
				2	32	14				
(Note:	Operating	3 cells)		3	--	--				
				4	32	14				
				5	--	--				

APPENDIX F
HEAVY METALS EMISSIONS DATA SUMMARIES

TABLE F-1. AA ANALYSIS OF AEROSOL CAPTURE FOR COAL-ONLY (1:0) FIRING

$\mu g/m^3$		Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
Part Filter														
4-34	3/19	156	2.60	168	<0.69	29.8	24.2	26.0	474.	33.5	1.86	<37.2	<3.72	37.2
4-35	3/19	254	4.54	439		27.3	18.4	46.3	613.	45.4	1.82	<90.9	<9.09	90.9
4-37	3/21	147	2.62	237.		36.7	34.0	59.7	445.	41.9	.524	<52.4	<5.24	<52.4
4-38	3/22	758	2.43	115.		36.4	30.3	41.9	531	42.5	1.21	<60.7	<6.07	<60.6
4-39	3/28	169	<3.38	143	<0.56	22.5	28.2	37.2	507	<56.3	1.13	<113.	<11.3	<113
4-40	3/31	190	7.15	65.6	<1.03	7.95	15.9	21.5	397	<39.7	<.79	< 79.5	<7.9	<79.5
4-41	3/31	190	2.38	87.3	<0.99	11.9	23.8	22.2	337	<39.7	<.79	< 79.3	<7.93	<79.3
4-42	4/1	200.	3.73	187.		58.6	40.0	59.2	546	<37.3	1.33	< 53.3	<5.33	<53.3
3-42	5/3	184	2.30	196.		69.0	65.2	29.9	115	38.3	.767	< 76.7	<7.67	<76.7
3-43	5/4	165	2.35	162		20.6	35.3	24.7	<58.9	35.3	.883	< 58.9	<5.89	<58.9
3-44	5/5	222	3.13	195.		287.	36.5	20.4	679.	52.3	1.57	< 52.2	<5.22	52.3
3-45	5/5	369	5.76	199		60.2	60.2	31.9	1047.	68.0	3.14	< 52.3	<5.23	52.3
3-46	5/16	144	2.41	76.8		12.0	11.4	27.5	337	24.1	.722	< 48.2	<4.82	<48.2
3-47	5/16	517	8.01	151		32.8	34.3	28.8	713	51.2	1.19	< 32.0	<3.20	37.0
3-48	5/17	116	2.00	71.2		46.0	35.6	10.4	286.	24.9	<.498	< 49.5	<5.0	<50.0
Probe Wash														
4-51	3/19	28.1	4.02	184.5		44.7	5.43	17.5	101.	12.1		< 10.1	<13.7	10.1
4-53	3/22		1.32	44.2		25.7	31.2	9.99	53.8	7.05	.277	< 6.94	<9.71	<7.05
4-54	3/22	13.8	2.07	45.3		82.5	88.9		346	7.90	.296	< 9.86	< .988	<9.9
4-55	3/28	18.7	1.40	38.5		409.	5253.	62.1	105	21.0	.467	< 23.3	<2.33	<23.3
4-56	3/31	32.3	1.59	23.7		74.7	67.9	13.6	70.8	5.66	.509	< 11.3	<1.13	<11.3
4-57	3/31	27.4	.697	13.1		38.3	44.8	8.07	47.3	<4.98	.300	< 9.96	< .996	<9.96
4-58	4/1	17.8	1.02	11.2		44.1	37.1	10.2	42.4	3.96		< 5.66	<1.13	<5.66
3-38	Composite May	16.1	2.15	16.1		134.2	183.	--	56.4	6.4	.107	< 1.08	< .537	<5.37

TABLE F-2. AA ANALYSIS OF AEROSOL CAPTURE OF 1:1 BLEND FIRING

μg/m^3		Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sa	Sb	Ag	Vn
Part. Filter														
4-43	3/23	2705.	69.1	55.1		25.0	27.6	43.6	6011	75.1	2.50	<50.1	10.5	<50.1
4-44	3/23	4638	84.3	46.7	<0.65	37.1	34.5	78.0	5994	101.	4.77	<53.0	12.7	<53.0
4-45	3/24	3492	62.8	23.4	<0.54	29.1	25.2	54.6	4341	85.3	1.94	<38.8	9.30	<38.8
3-49	5/12	5609	74.5	159.		33.5	37.7	62.8	5441	83.7	3.35	<41.9	8.37	<41.8
3-50	5/12	2847	64.0	165.	<0.68	28.9	31.1	64.0	4892	66.7	2.67	<44.5	<4.45	<44.5
3-51	5/13	2438	47.6	64.5	<0.50	29.5	23.6	33.0	4325	62.9	.786	<39.3	<3.93	<39.3
Probe Wash														
4-59	3/23	78.1	2.09			34.5	35.6	18.4	207	5.23	.418	<10.5	2.09	<10.5
4-60	3/23	112.	1.68			11.2	11.2	6.14	196	<27.9	<.559	<55.9	<5.59	<55.9
4-61	3/24	122.	2.34			13.2	22.0	11.0	173	<14.6		<29.3	<2.93	<29.3
3-39	Composite May	108	2.16			13.5	116.	10.2	132.	7.73	.232	<7.73	<.773	<7.73

TABLE F-3. AA ANALYSIS OF AEROSOL CAPTURE FOR 1:2 BLEND FIRING

$\mu g/m^3$		Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
Part. Filter														
4-46	3/29	10,140.	269.	60.6		38.6	35.8	72.7	11020	110	2.2	<55.1	23.7	<55.1
4-47	3/29	5,151.	216.	23.3	<0.65	43.7	14.6	76.3	3686	36.9	2.13	<89.9	11.7	<19.4
4-48	3/30	3,621.	94.0	36.5	<0.90	34.8	48.7	98.2	6264	55.7	7.66	<69.6	6.96	<69.6
3-52	5/10	6,345.	162	103		61.3	78.3	96.4	7191	140.	2.33	<42.3	19.5	<42.3
3-53	5/10	5,595.	275	105	<0.80	39.6	29.7	107.	6435	94.1	4.46	<49.5	13.9	<49.5
3.54	5/11	7,893.	90.5	95.5		35.2	20.1	75.4	6539	95.5	1.51	<50.3	14.1	<50.3
Probe Wash														
4-62	3/29	337	6.59	12.1		161	130.	31.2	295.	<17.4	.347	<34.7	< 3.47	<34.7
4-63	3/29	218	5.41	12.2		79.6	78.1	60.4	263.	<15.0	2.11	<30.1	<3.01	<30.1
4-64	3/30	249	4.04	4.7		49.4	67.4	29.7	371.	<22.5	1.35	<44.9	<4.49	<44.9
3-40	Comp May	257	5.82	20.4		68.0	113.	20.6	318.	12.1	.605	<7.56	<.756	<7.56

TABLE F-4. AA ANALYSIS OF AEROSOL CAPTURE FOR 0:1 BLEND FIRING

$\mu g/m^3$	Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
Part. Filter													
3-55 5/14	9557	240	39.5	<1.06	60.8	26.1	200.	>821	165.	3.48	<86.9	24.3	<86.9
3-56 5/14	6351	187	39.6		66.9	20.9	241	5016	159.	6.27	<83.6	23.4	<83.6
Probe Wash Composite May	326	15.8	11.8		34.0	31.3	--	605	21.8	.816	<27.2	<2.7	<27.2

TABLE F-5. AA ANALYSIS OF ASH SAMPLES FROM 1:0 FIRING

	Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn
B.A.	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
4-66 3/28	<12.5	<.75	11.0	<0.4	22.5	20.0	51.0	31.2	15.0	.50	<25	<2.5	<25
3-111 5/3	<12.5	<.75	17.9	<0.4	10.0	23.7	40.5	37.5	25.0	--	<25	5.75	<25
3-105 5/17	<12.5	<.75	14.3	<0.4	7.5	16.2	40.5	100.	<12.5	.50	<25	120.	<25
F.A. Coll #1	30.0	<.75	102.4	<0.4	20.0	37.5	69.7	50.0	20.0	2.38	<25	<2.5	25.0
3-107 5/4	17.5	<.75	77.0	<0.4	15.0	25.0	42.0	81.2	12.5	2.13	<25	<2.5	25.0
3-84 5/5	15.0	<.75	49.5	<0.4	18.1	25.0	37.5	50.0	12.5	1.75	<25	<2.5	25.0
3-99 5/17													
F.A. Reinj #2													
~~4-70 $\overline{a+b}$ 3/28~~	~~134.2~~	~~2.87~~	~~625.~~	~~<0.4~~	~~25.0~~	~~25.6~~	~~300~~	~~306.~~	~~27.5~~	~~2.37~~	~~<25~~	~~<2.5~~	~~3.0~~
4-68 3/31	16.3	<.75	34.4	<0.4	8.75	15.0	105	31.2	<12.5	1.88	<25	<2.5	<25
3-83 5/3	20.0	<.75	48.1	<0.4	21.3	26.2	45.0	50.0	15.0	1.0	<25	<2.5	25.0

Notes: B.A. denotes bottom ash and F.A. denotes fly ash.

TABLE F-6. AA ANALYSIS OF ASH SAMPLES FROM 1:1 FIRING

B.A.		Pb mg/kg	Cd mg/kg	As mg/kg	Hg mg/kg	Cr mg/kg	Ni mg/kg	Mn mg/kg	Zn mg/kg	Cu mg/kg	Sn mg/kg	Sb mg/kg	Ag mg/kg	Vn mg/kg
3-102	5/12	36.3	.75	40.0	<0.4	25.0	40.0	185.	150.	218.	2.63	<25	<2.5	<25
3-103	5/13	56.3	<.75	30.0	<0.4	22.5	26.2	155.	75.0	225.	4.0	<25	<2.5	<25
4-67	3/23	26.3	<.80	39.3	<0.4	25.6	27.4	138.	73.3	152.	3.58	<25	<2.5	<25.5
F.A. Coll #1														
3-85	5/9	148.	1.75	50.0	≤0.4	20.6	25.0	101	197	<15.0	2.13	<25	<2.5	<25
3-91	5/12	250.	4.7	100.	≤0.75	22.5	35.0	197.	431	40.0	4.38	<25	<2.5	35
3-92	5/12	300.	5.37	124.	≤0.5	23.1	35.0	196.	512	36.3	5.3	<25	<2.5	30
3-93	5/13	168.	2.5	47.5	0.53	12.5	21.2	86.3	231	20.0	2.5	<25	<2.5	<25
F.A. Reinj. #2														
4-72	3/23	97.5	1.25	38.5	0.68	13.8	17.5	161	125.	15.0	2.0	<25	<2.5	25.0
4-71	3/24	97.5	1.0	39.0	~~3.65~~	11.3	16.2	225	144.	15.0	3.0	<25	<2.5	<25
3-94	5/13	92.5	1.0	49.5	0.58	21.3	23.7	120	156.	22.5	3.0	<25	<2.5	25.0

Notes: B.A. denotes bottom ash, F.A. denotes fly ash, and ≤ represents that the number reported is an average of two in which one was below the detection limit and the other was just above.

TABLE F-7. AA ANALYSIS OF ASH SAMPLES FROM 1:2 FIRING

BA		Pb mg/kg	Cd mg/kg	As mg/kg	Hg mg/kg	Cr mg/kg	Ni mg/kg	Mn mg/kg	Zn mg/kg	Cu mg/kg	Sn mg/kg	Sb mg/kg	Ag mg/kg	Vn mg/kg
4-65	3/30	128	.75	36.7	<0.4	42.5	139	250	188.	200	5.0	<25	<2.5	<25
3-100	5/10	47.5	.75	30.2	<0.4	18.8	16.3	135	81.2	~~1150~~	3.0	<25	<2.5	<25
3-101	5/11	82.5	.75	27.5	<0.4	22.5	27.8	135	65.6	186	4.25	<25	<2.5	<25
F.A. Coll #1														
3-86	5/10	275	5.75	49.5	<0.4	26.1	22.0	317.	598	29.7	1.08	<27.5	<2.5	27
3-89	5/11	246	6.25	37.5	<0.4	38.7	37.5	379.	619.	50.0	2.69	<25	<2.5	30
3-90	5/11	300	6.0	--	2.3	40.	36.2	288.	606	40.	1.13	<25	<2.5	25
F.A. Reinj #2														
4-69	3/29	109	1.5	66	<0.4	15.0	18.7	300	194	17.5	2.25	<25	<2.5	25.
3-87	5/10	132	1.3	32.4	≤0.43	28.4	20.2	146.	203	24.3	--	<27	<2.7	<27
3-88	5/11	198	2.5	37.5	<0.4	18.7	26.2	250	381.	60	3.0	<25	<2.5	25.

Notes: B.A. denotes bottom ash, F.A. denotes fly ash, and ≤ represents that the number reported is an average of two in which one was below the detection limit and the other was just above.

TABLE F-8. AA ANALYSIS OF ASH SAMPLES FROM 0:1 FIRING

B.A.	Pb mg/kg	Cd mg/kg	As mg/kg	Hg mg/kg	Cr mg/kg	Ni mg/kg	Mn mg/kg	Zn mg/kg	Cu mg/kg	Sn mg/kg	Sb mg/kg	Ag mg/kg	Vn mg/kg
3-104 5/14	169.	2.125	56.3	≤0.4	50.0	35.0	43.5	539.	205	3.6	<25	88.8	<25
F.A. Coll #1													
3-96 5/14	925.	26.0	122.	≤0.5	176.	82.9	130.	--	176.	11.3	<25.	12.7	40.0
3-97 5/14	1100.	24.8	85.3	0.61	193.	68.8	117.	--	127.	4.86	<27.5	14.8	43.2
F.A. Reinj #2													
3-95 5/14	350	8.50	52.5	≤0.48	65.0	45.0	82.3	1138.	95.0	4.38	<25	6.5	25.0
3-98 5/14	375	7.25	40.0	≤0.4	73.7	36.9	80.3	1097.	81.7	5.3	<25	5.5	≤25.

Notes: B.A. denotes bottom ash, F.A. denotes fly ash, and ≤ represents that the number reported is an average of two in which one was below the detection limit and the other was just above.

TABLE F-9. TOTAL METAL EMISSION RATE IN THE FLUE GAS

		TOTAL PARTICULATE $\mu g/m^3$								P.F. $\mu g/m^3$		Tot Part g P.F.g				
		Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn	Total Part.	Part. Filter
March 1:0																
4-34	3/19	202	3.37	218	11.1	38.7	31.4	33.7	615	43.5	2.41	<48.3	<4.83	48.3	.8215	.6329
4-35	3/19	327	5.85	~~565~~	9.4	35.2	23.7	59.6	790.	58.5	2.34	<117.	<11.7	117	.5618	.4361
4-37	3/21	171	3.05	276.	10.4	42.7	39.6	69.5	518	48.7	0.610	<61.0	<6.10	<61	.6814	.5857
4-38	3/22	~~961~~	3.08	146.	8.0	46.2	38.4	53.1	673	53.9	1.53	<77.0	<7.70	<77.0	.4946	.3901
4-39	3/28	220	<4.40	186.	<5.3	29.3	36.7	48.4	660	<73.3	1.47	<147	<14.7	<147	.2203	.1692
4-40	3/31	233	8.76	80.4	3.3	9.74	19.5	26.3	486	<48.6	<.968	<97.4	<9.74	<97.4	.3747	.3059
4-41	3/31	218	2.73	100.	<8.1	13.6	27.3	25.4	386	<45.5	<.905	<90.9	<9.09	<90.9	.3851	.3361
4-42	4/1	222	4.14	208.	7.2	65.1	44.4	65.7	606	41.4	1.48	<59.2	<5.92	<59.2	.5850	.5268
	$\overline{X}$	228	≤4.43	173	≤7.85	35.1	32.6	47.7	592	≤51.7*	<1.46	<87.2	<8.72	<87.2		
May 1:0																
3-42	5/3	295	3.69	315	<8.1	111.	105.	48.0	185.	61.5	1.23	123.	<12.3	<12.3	.4090	.2548
3-43	5/4	210	2.99	206.	6.0	26.2	45.0	31.5	~~<75~~	45.0	1.10	<75.	<7.5	< 7.5	.5716	.4488
3-44	5/5	242.	3.42	213.	2.8	~~313~~.	39.9	22.3	742	57.1	1.71	<57.0	<5.70	<57.0	.6955	.6368
3-45	5/5	333	6.21	215.	4.8	64.9	64.9	34.4	1129	73.3	3.39	<56.3	<5.63	<56.3	.6578	.6101
3-46	5/16	171	2.86	91.0	<5.1	14.2	13.5	32.6	399.	28.6	.855	<57.1	<5.71	<57.1	.9075	.7660
3-47	5/16	~~579~~	8.98	169.	7.3	36.8	38.4	32.3	799.	57.4	1.33	<35.9	<3.59	<35.9	1.0586	.9447
3-48	5/17	129	2.23	79.4	<4.9	51.3	39.7	11.6	319.	27.8	<.555	<55.2	<5.57	<55.7	.6837	.6131
	$\overline{X}$	230	4.33		≤5.57	50.7	49.5	30.4	596	50.1	≤1.45	<65.6	<6.56	<65.6		

(continued)

TABLE F-9. (continued)

								TOTAL PARTICULATE µg/m³			PF µg/m³		Tot Part g / PFg			
		Pb	Cd	As	Hg	Cr	Ni	Mn	Zn	Cu	Sn	Sb	Ag	Vn	Total Part.	Part. Filter
March 1:1																
4-43	3/23	3035	77.5	61.8	21.3	28.0	31.0	48.9	6744	84.3	2.80	<56.2	11.8	<56.2	.4104	.3658
4-44	3/23	4917	89.4	49.5	11.1	39.3	36.6	82.7	6354	107	5.06	<56.2	13.5	<56.2	.4923	.4644
4-45	3/24	3973	71.4	26.6	26.5	33.1	28.7	62.1	4939	97	2.21	<44.1	10.6	<44.1	.5222	.4590
	$\overline{X}$	3975	79.4	45.9	19.6	33.5	32.1	64.6	6012	96.1	3.36	<52.2	12.0	<52.2		
May 1:1																
3-49	5/12	6656	88.4	189.	20.0	39.8	44.7	74.5	6457	99.3	3.98	<49.7	9.93	<49.7	.7092	.5976
3-50	5/12	3512	79.0	204	15.0	35.7	38.4	79.0	6035	82.3	3.29	<54.9	<5.49	<54.9	.7000	.5674
3-51	5/13	2543	49.7	673	12.2	30.8	24.6	34.4	4512	65.6	0.82	<47.0	<4.10	<41.0	.4035	.3868
	$\overline{X}$	4237	72.4	153	15.7	35.4	35.9	62.6	5668	82.4	2.70	<48.5	≤6.51	<48.5		
March 1:2																
4-46	3/29	12289	326.	73.4	15.4	46.8	43.4	88.1	13355	133	2.67	<66.8	28.7	<66.8	.4518	.3728
4-47	3/29	6054	254	27.4	14.7	51.4	17.2	89.7	4332	43.4	2.50	106.	13.8	<22.8	.4694	.3994
4-48	3/30	4636	120	33.9	6.9	44.6	62.3	126.	8020	71.3	9.81	<89.1	8.91	<89.1	.2845	.2222
	$\overline{X}$	7660.	233	44.9	12.3	47.6	41.0	101	8569	82.5	4.99	≤87.3	17.1	<59.6		
May 1:2																
3-52	5/10	7116.	182	116.	13.7	68.8	87.8	108.	8065	157.	2.61	<47.4	21.9	<47.4	.8542	.7616
3-53	5/10	7338	361	138	9.1	51.9	38.9	140	8440	123	5.85	<64.9	18.2	<64.9	.7227	.5510
3-54	5/11	10196	117	123	11.5	45.5	26.0	97.4	8447	123	1.95	<65.0	18.2	<65.0	.5889	.4559
	$\overline{X}$	8217	220	126	11.4	55.4	50.9	115.	8317	134	3.47	<59.1		<59.1		
May 0:1																
3-55	5/14	12046	303	49.8	90.8	76.6	32.9	252.	9858	208	4.38	<109.	30.6	<109	.3518	.2791
3-56	5/14	7859	231	49.0	98.6	82.8	25.9	298	6207	197	7.76	<103	28.9	<103	.3246	.2623
	$\overline{X}$	9953.	267	49.4	94.7	79.7	29.4	275	8033	203	6.07		29.7			

Notes: B.A. denotes bottom ash, F.A. denotes fly ash, and ≤ represents that the number reported is an average of two in which one was below the detection limit and the other was just above.

APPENDIX G

PHYSICAL AND CHEMICAL CHARACTERIZATION OF RDF/COAL FLY ASH

INTRODUCTION

As part of the effort to identify the potential for environmental impact by fly ash generated by combustion of a coal:dRDF blend, fly ash samples were sent to Colorado State University for analysis. The aims of this testing were to identify any differences in the composition of fly ash generated by different coal:dRDF fuels, to ascertain whether concentrations of certain materials existed at the surface of the particles, and to determine if fly ash composition was a function of particle size. D. F. S. Natusch of Colorado State University was selected to perform the analysis because of his extensive background in this area. The tentative conclusions put forth in this section are the result of Dr. Natusch's analysis.

Specifically, the investigation was designed to answer the following questions:

1. What are the morphological and compositional characteristics of fly ash generated by burning dRDF:coal fuel blends?

2. What is the elemental composition of fly ash generated by burning dRDF:coal fuel blends with respect to (a) the size of the particles and (b) the ratio of dRDF to coal?

3. What factors appear to be responsible for the partitioning of elements present in the fly ash as a function of size and RDF content?

4. To what extent can individual elements present in the fly ash be mobilized into solution as a result of an aqueous leaching process?

In the following sections we present a brief description of the analytical methodology employed, a list of the results obtained, and a short discussion of the meaning of these results.

PHYSICAL CHARACTERISTICS OF RDF/COAL FLY ASH

The samples of dRDF:coal fly ash received consisted of four sets of seven samples. Each sample set was obtained from burning a different ratio of dRDF to coal ranging from pure coal to pure dRDF, and the seven samples corresponding to each set were obtained from the seven impaction stages of an

MRI stack sampler. Each of the seven impactor stages for each blend ratio consisted of composited scrapings from two to six stack samples. The distribution of particle mass within this 28-sample set is presented elsewhere in this report.

Each of the 28 subsamples was investigated using a scanning electron microscope (Hitachi, Model HHS-2R). Each sample was mounted on double-sided Scotch tape and coated with carbon and gold for the purpose of observation.

The results showed the fly ash to consist of four different structural types. The first type consisted of a "spongy-looking" material that may have been formed as a result of condensation or agglomeration of extremely small particles onto the surface of large particles (Figure G-1). The second type was in the form of extremely thin sheets, some of which were found to roll or unroll under the influence of the SEM electron beam (Figure G-2). The third type was spherical in form and similar to conventional fly ash particles obtained from the combustion of coal. It is interesting to note, however, that the size distribution, as observed qualitatively under the microscope, indicated that these spherical particles are significantly smaller than those normally found in a conventional coal-fired power plant. In addition, it was noted that even when pure coal was employed as fuel, the geometry of the so-called spherical fly ash particles was significantly different from those obtained in a full-size power plant, indicating that combustion conditions employed in this particular experimental unit were, in fact, somewhat unique (Figure G-3). The fourth type of particle was in the form of flaky material (Figure G-4) with somewhat rounded edges which indicate the possibility of some melting during the combustion process.

It was observed that each of these morphological types was present in all of the subsamples investigated. There were, however, some variations in the relative amounts of each structure obtained in particular subsamples. For example, the spherical particles were found to occur in much greater profusion in the small size fractions of the samples from the 1:1 and 1:2 RDF-to-coal blends.

It is apparent from the foregoing results that fly ash generated from burning blends of dRDF:coal is significantly different in form from that which results from the combustion of pure coal. In particular, the absence of a large population of spherical particles indicates that the combustion temperature employed in this particular system was insufficient to generate molten fly ash material as occurs in the combustion zone of conventional coal-fired units. This phenomenon provides relatively high specific surface areas due to the predominance of the spongy-type material illustrated in Figure G-1, and consequently the operation of strong surface-associative effects in the distribution of potentially toxic species might be expected.

The second type of physical characterization performed was a determination of the distribution of the specific surface area of the fly ash particles as a function of both particle size and the dRDF:coal ratio. This was achieved using a Quantachrome Quantasorb Model QS-7 which enables determination of a specific BET surface area based on the adsorption of nitrogen. Under normal operating conditions, samples are initially outgassed at 300°C

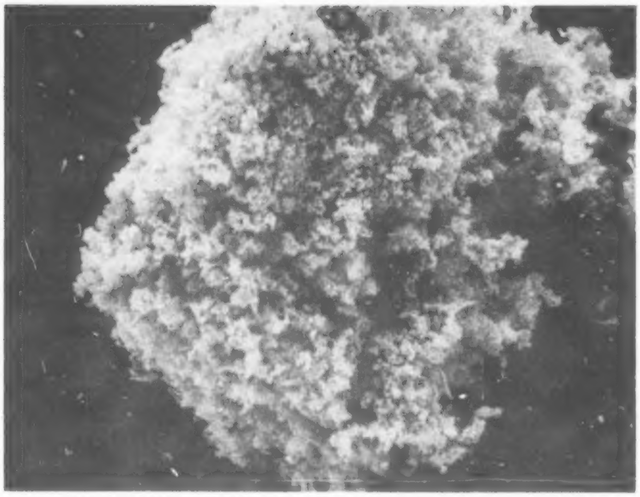

Figure G-1. 0% RDF sample, S4, magnification 450 X.
(Note spherical particle at about 4 o'clock)

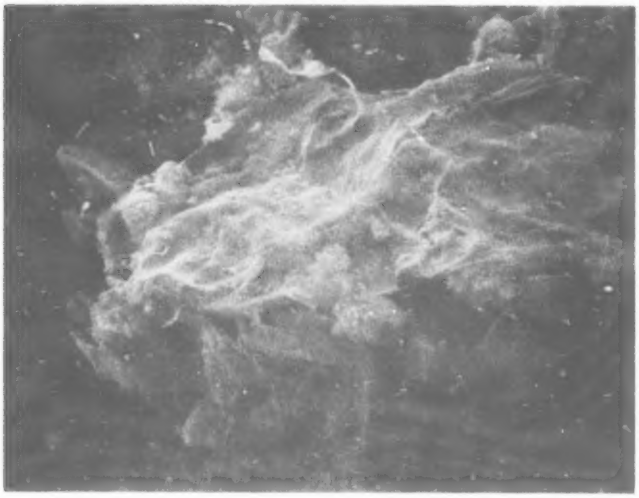

Figure G-2. 67% RDF sample, S4, magnification 3500 X.

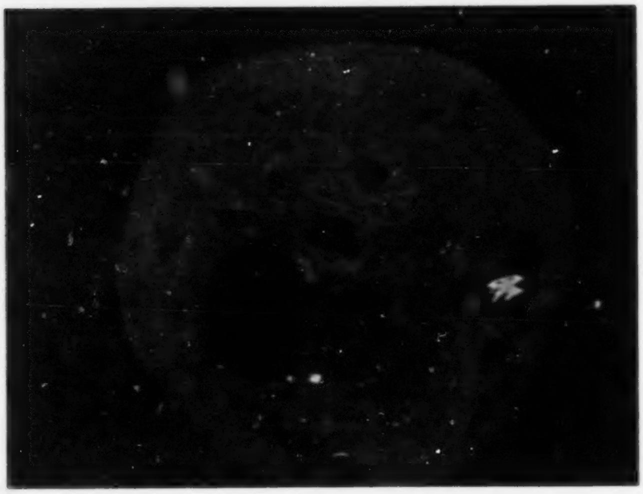

Figure G-3. 100% RDF sample, S4, magnification 10,000 X.

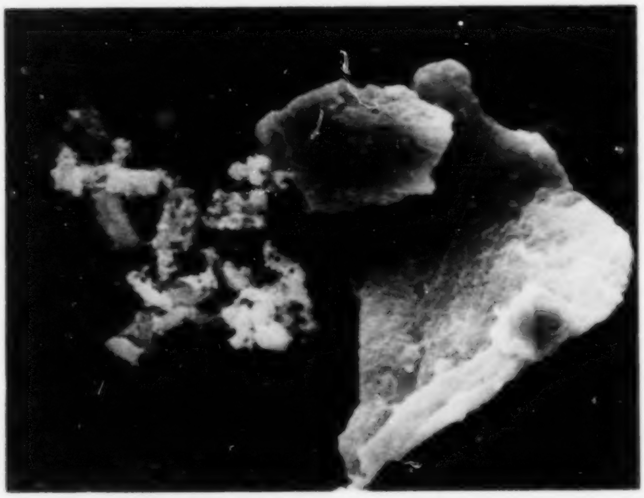

Figure G-4. 50% RDF sample, S4, magnification 2000 X.

to remove any absorbed material prior to the determination of the surface area. Due to lack of material, however, outgassing at 300°C was not employed in the present instance for fear of losing potentially volatile elements such as arsenic and cadmium. For this reason, outgassing at room temperature was employed with the result that the samples were not, in our opinion, completely outgassed. Nevertheless, the specific surface area values obtained are considered to be relatively consistent within the individual sample set investigated. They should not, however, be taken as absolute values.

The results obtained are illustrated in Table G-1 from which it will be seen that insufficient material was available for determination of all size fractions and dRDF:coal ratios. Nevertheless, the results do establish several points of interest. First, it is apparent that the stack sampler employed for particle collection in this study is, in fact, producing a good differentiation of the fly ash on the basis of particle size. In other words, there is a clear dependence of the specific surface area of these particles on aerodynamic particle size. Secondly, there appears to be a general trend of increasing specific surface area with increasing RDF-to-coal content. In short, the higher the RDF content of the fuel the greater the specific surface area of the fly ash particles which result.

TABLE G-1. SURFACE AREAS (m^2/g) OF dRDF:COAL FLY ASH FOR THE SEVEN SIZE FRACTIONS COLLECTED USING AN MRI STACK SAMPLER

dRDF by volume	Size fraction S1	S2	S3	S4	S5	S6	S7
0%	---	---	4.96	5.73	8.38	10.2	10.1
50%	---	---	7.26	9.02	---	9.90	---
67%	---	---	---	9.61	11.4	---	---
100%	2.7	5.5	15.3	17.9	20.8	23.0	30.0

←Increasing size

Table G-2 presents the size fraction cut-off for each of the impactor plates (S1 through S7). For example, Stage S2 is 50 percent efficient in collecting particles in the size range of 15 to 30 microns.

TABLE G-2. NOMINAL CUT DIAMETERS FOR IMPACTOR TESTS

Stage	Partical Size at 50 Percent Efficiency (microns)
S1	30
S2	15
S3	6
S4	2.4
S5	1.5
S6	0.65
S7	0.37
Filter	Less than 0.37

NOTE: For further information see Meteorology Research, Inc., Instruction Manual, Inertial Cascade Impactor, Model 1502 and 1503, 1976.

ELEMENTAL COMPOSITION

Elemental analyses of the various subsamples presented were carried out in several ways. Semiquantitative analysis of a number of the samples was undertaken using direct current arc emission spectrometry in which the spectra were recorded photographically on a Baird-Atomic 3-meter grating spectrometer, Model 6X-1. Samples were mixed with "Spex Mix" spectroscopic graphite using a "wig-L-bug" and were completely vaporized using a direct current arc. The integrated spectra obtained were analyzed using a manual densitometer. The results obtained for the S3 size fraction are presented in Table G-3.

Samples were digested in an acid mixture consisting of 3.5 mls of aqua regia, 2.5 mls of 48 percent hydrofluoric acid, and 0.5 mls of water. The resulting digest was neutralized using approximately 2 grams of boric acid to remove excess hydrofluoric in the form of boron trifluoride. These samples were then analyzed for 18 elements using an automated Spectrometrics plasma emission spectrometer utilizing an Echelle monochromator. The results reported by element are listed in Table G-3.

Specific analyses for arsenic were performed by generating the arsenic hydride and identifying this concentration using conventional flame atomic absorption spectrometry. The results obtained for arsenic are also included in Table G-3.

TABLE G-3. ELEMENTAL ANALYSIS OF INDIVIDUAL RDF COAL FLY ASH SAMPLES CONCENTRATIONS IN μg/g

Element	dRDF by Volume	Analysis Method	Size Fraction From Sampler S1	S2	S3	S4	S5	S6	S7
Aluminum									
	0%	PES				84,000			
		INAA							
		DCAES							
	50%	PES			57,900	9,970			
		INAA							
		DCAES							
	67%	PES				101,000	55,900		
		INAA							
		DCAES							
	100%	PES			44,300	46,400	42,700	41,200	
		INAA							
		DCAES							
Antimony									
	0%	PES							
		INAA				58			
		DCAES			(1)				
	50%	PES							
		INAA				200			
		DCAES			(5)				
	67%	PES							
		INAA				341			
		DCAES			(10)				
	100%	PES							
		INAA	22	24	31	3.2*	5.5*	5.8*	111
		DCAES			(20)				

(continued)

TABLE G-3. (continued)

	dRDF	Analysis	Size Fraction from Sampler						
Element	by Volume	Method	S1	S2	S3	S4	S5	S6	S7
Arsenic									
	0%	AAS							
		INAA							
		DCAES			(400)				
	50%	AAS							
		INAA							
		DCAES			(300)				
	67%	AAS							
		INAA							
		DCAES			(350)				
	100%	AAS			500	1150	461	1700	1000
		INAA	312	548	888	1211	1392	1571	691
		DCAES			(200)				
Barium									
	0%	PES				1220			
		INAA				762			
		DCAES							
	50%	PES			1630	1230			
		INAA				488			
		DCAES							
	67%	PES				1530	1220		
		INAA				959			
		DCAES							
	100%	PES			992	1050	1390	679	
		INAA	<105	<334	1100	1042	881	1050	252
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	Size Fraction from Sampler S1	S2	S3	S4	S5	S6	S7
Beryllium									
	0%	PES				21.7			
		INAA							
		DCAES			(9)				
	50%	PES				9.15			
		INAA							
		DCAES			(9)				
	67%	PES			<53.4	<29.0	42.6		
		INAA							
		DCAES			(7)				
	100%	PES			13.0	3.27	18.9	<36.2	
		INAA							
		DCAES			(10)				
Bromine									
	0%	PES							
		INAA				85.			
		DCAES							
	50%	PES							
		INAA				229			
		DCAES							
	67%	PES							
		INAA				357			
		DCAES							
	100%	PES							
		INAA	973	256	107	146	95	140	110
		DCAES							

(continued)

TABLE G-3. (continued)

	dRDF	Analysis	Size Fraction from Sampler						
Element	by Volume	Method	S1	S2	S3	S4	S5	S6	S7
Cadmium									
	0%	PES				139			
		INAA							
		DCAES			(3)				
	50%	PES			<931	<108			
		INAA							
		DCAES			(20)				
	67%	PES				<505	394		
		INAA							
		DCAES			(20)				
	100%	PES			<92.1	<116	<167	<631	
		INAA							
		DCAES			(3)				
Calcium									
	0%	PES							
		INAA				16,700			
		DCAES							
	50%	PES			41,000	14,100			
		INAA							
		DCAES							
	67%	PES				32,400	27,000		
		INAA							
		DCAES							
	100%	PES			12,000	14,000	9,750	10,500	
		INAA							
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	Size Fraction from Sampler S1	S2	S3	S4	S5	S6	S7
Chromium									
	0%	PES							
		INAA							
		DCAES			(150)				
	50%	PES							
		INAA							
		DCAES			(300)				
	67%	PES							
		INAA							
		DCAES			(300)				
	100%	PES							
		INAA							
		DCAES			(70)				
Cobalt									
	0%	PES							
		INAA							
		DCAES			(60)				
	50%	PES							
		INAA							
		DCAES			(50)				
	67%	PES							
		INAA							
		DCAES			(30)				
	100%	PES							
		INAA							
		DCAES			(60)				

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	Size Fraction from Sampler						
			S1	S2	S3	S4	S5	S6	S7
Copper									
	0%	PES				91.3			
		INAA							
		DCAES			(100)				
	50%	PES			<3,630	<283			
		INAA							
		DCAES			(60)				
	67%	PES				<134	<4,320		
		INAA							
		DCAES			(50)				
	100%	PES			<747		<1,780	<168	
		INAA							
		DCAES			(100)				
Dysprosium									
	0%	PES							
		INAA				18.2			
		DCAES							
	50%	PES							
		INAA				10.9			
		DCAES							
	67%	PES							
		INAA				7.5			
		DCAES							
	100%	PES							
		INAA	<0.039	5.0	9.7	11.1	10.5	10.0	3.9
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	S1	S2	S3	S4	S5	S6	S7
			Size Fraction from Sampler						
Europium									
	0%	PES							
		INAA				3.13			
		DCAES							
	50%	PES							
		INAA				2.2			
		DCAES							
	67%	PES							
		INAA				1.55			
		DCAES							
	100%	PES							
		INAA	<0.37	<0.74	1.79	1.93	1.90	2.08	0.73
		DCAES							
Gallium									
	0%	PES							
		INAA				120			
		DCAES							
	50%	PES							
		INAA				80			
		DCAES							
	67%	PES							
		INAA				49			
		DCAES							
	100%	PES							
		INAA	32	22	69	80	114	173	165
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	S1	S2	S3	S4	S5	S6	S7
Lanthanum									
	0%	PES							
		INAA				68			
		DCAES							
	50%	PES							
		INAA				60			
		DCAES							
	67%	PES							
		INAA				41			
		DCAES							
	100%	PES							
		INAA	9.3	19	46	37	49	48	25
		DCAES							
Lead									
	0%	PES			<10,400	757			
		INAA							
		DCAES			(300)				
	50%	PES				189			
		INAA							
		DCAES			(800)				
	67%	PES				<7,830	<7,745		
		INAA			(1,000)				
		DCAES							
	100%	PES			<1,030	<1,290	<1,860	<7,042	
		INAA							
		DCAES			(500)				

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	Size Fraction from Sampler S1	S2	S3	S4	S5	S6	S7
Magnesium									
	0%	PES				4,000			
		INAA							
		DCAES							
	50%	PES			7,260	4,550			
		INAA							
		DCAES							
	67%	PES				6,810	6,630		
		INAA							
		DCAES							
	100%	PES			3,680	4,060	2,970	2,910	
		INAA							
		DCAES							
Maganese									
	0%	PES				<391			
		INAA				378			
		DCAES			(300)				
	50%	PES			<4,530	<548			
		INAA				555			
		DCAES			(300)				
	67%	PES				<257			
		INAA				741			
		DCAES			(400)				
	100%	PES			<3,260	<58.5		<321	
		INAA	947	666	206	189	183	167	79
		DCAES			(200)				

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	S1	S2	S3	S4	S5	S6	S7
					Size Fraction from Sampler				
Molybdenum									
	0%	PES				<13.5			
		INAA							
		DCAES							
	50%	PES				<18.9			
		INAA							
		DCAES							
	67%	PES				<88.6			
		INAA							
		DCAES							
	100%	PES				<20.3		<111	
		INAA							
		DCAES							
Nickel									
	0%	PES							
		INAA							
		DCAES			(1,000)				
	50%	PES			7,260				
		INAA							
		DCAES			(600)				
	67%	PES							
		INAA							
		DCAES			(600)				
	100%	PES			4,610		<37,200	214	
		INAA							
		DCAES			(300)				

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	Size Fraction from Sampler						
			S1	S2	S3	S4	S5	S6	S7
Phosphorous									
	0%	PES				3,710			
		INAA							
		DCAES							
	50%	PES			<11,900	2,340			
		INAA							
		DCAES							
	67%	PES				3,260	3,450		
		INAA							
		DCAES							
	100%	PES			1,360	1,770	887	1,360	
		INAA							
		DCAES							
Potassium									
	0%	PES				18,400			
		INAA				12,900			
		DCAES							
	50%	PES			20,800	15,900			
		INAA				18,000			
		DCAES							
	67%	PES				17,000	26,200		
		INAA				15,900			
		DCAES							
	100%	PES			13,300	15,600	11,400	10,000	
		INAA	2,500	3,000	1,010	11,600	11,500	11,800	5,400
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	S1	S2	S3	S4	S5	S6	S7
Silicon									
	0%	PES				74,600			
		INAA							
		DCAES							
	50%	PES							
		INAA							
		DCAES							
	67%	PES				33,000			
		INAA							
		DCAES							
	100%	PES			19,000	88,900			
		INAA							
		DCAES							
Sodium									
	0%	PES				24,300			
		INAA				3,300			
		DCAES							
	50%	PES				1,960			
		INAA				28,200			
		DCAES							
	67%	PES				45,600	4,000		
		INAA				28,200			
		DCAES							
	100%	PES			2,920	23,500			
		INAA	1,990	1,470	2,680	2,930	3,000	3,350	1,720
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	Size Fraction from Sampler S1	S2	S3	S4	S5	S6	S7
Strontium									
	0%	PES				1,180			
		INAA				1,270			
		DCAES							
	50%	PES			<981	881			
		INAA				1,518			
		DCAES							
	67%	PES				943	479		
		INAA				1,237			
		DCAES							
	100%	PES			740	879	410	661	
		INAA	<161	<193	989	1,107	638	1,010	420
		DCAES							
Titanium									
	0%	PES							
		INAA							
		DCAES			(6,000)				
	50%	PES							
		INAA							
		DCAES			(12,000)				
	67%	PES							
		INAA							
		DCAES			(10,000)				
	100%	PES							
		INAA							
		DCAES							

(continued)

TABLE G-3. (continued)

Element	dRDF by Volume	Analysis Method	S1	S2	Size Fraction from Sampler S3	S4	S5	S6	S7
Thalium									
	0%	PES							
		INAA							
		DCAES			(0.5)				
	50%	PES							
		INAA							
		DCAES			(2.0)				
	67%	PES							
		INAA							
		DCAES			(0.6)				
	100%	PES							
		INAA							
		DCAES			(2.0)				
Vanadium									
	0%	PES							
		INAA							
		DCAES			(1,500)				
	50%	PES							
		INAA							
		DCAES			(500)				
	67%	PES							
		INAA							
		DCAES			(300)				
	100%	PES							
		INAA							
		DCAES			(800)				

NOTE: PES - Echelle Plasma Emission Spectrometry
INAA - Instrumental Neutron Activation Analysis
DCAES - DC Arc Emission Spectroscopy
AAS - Atomic Absorption Spectrometry

* These values may be low due to arsenic interference.

Selected fly ash samples were subjected to instrumental neutron activation analysis utilizing a Triga II reactor having a neutron flux at the sample of approximately 10^{12} neutrons/second/cm^2. Since the primary objective of this analysis was to obtain some relative measure of the accuracy of the other analytical techniques and, specifically, to determine the arsenic and antimony present, only a short irradiation was employed. Following removal from the reactor, the samples were analyzed using a Ge/Li detector in conjunction with a 4096 channel multichannel analyzer. The results were transferred to magnetic tape and analyzed using the PIDAQ program. These results are presented in Table G-3.

Finally, several subsamples were subjected to individual particle analysis using a Kevex Model 5000A X-ray energy dispersive spectrometer (XES) associated with the scanning electron microscope.

A total of 27 elements were determined using the techniques listed above. It will be noted that the analyses were not performed by X-ray fluorescence spectrometry as originally envisaged due to the small amounts of sample provided. This decision was reached after initial results indicated unacceptably low counting statistics for most elements. As a result, a semiquantitative screening analysis was performed using DC arc emission spectroscopy (DCAES). This technique was applied only to the size fraction S3 of each RDF:coal blend sample. The results are considered to have only an order of magnitude precision so are presented in brackets in Table G-3.

The size fractions S3 to S6 were analyzed by plasma emission spectrometry. The results were generally disappointing due to the high blank levels encountered. Consequently, only about half of the analyses performed are considered to be meaningful, and only those are included in Table G-4. (It will be noted that good analytical data were obtained for the aqueous leachates presented later since extensive acid digestion was not required.) The precision of the PES results is generally about 10 percent although in this complex analytical matrix accuracy for the trace elements Be, Cd, Cu, Pb, Mn, Mo, and Ni is likely to be considerably poorer.

Analyses performed by Instrumental Neutron Activation Analysis all have a precision (based on counting statistics) of less than 10 percent. The accuracy appears to be comparable. Precisions of 1 to 2 percent are associated with the results obtained for AS, Mn, and Na.

It will be noted that quite good agreement is obtained between the techniques employed for the elements As, Ba, K, and Sr. Agreement is poor for the other elements. It must be strongly stressed, however, that in situations such as this where the original samples are composites of grab samples, sampling statistics are normally extremely poor. Since different analytical techniques require different amounts of sample, this means that the precision associated with each procedure will vary greatly even though the intrinsic analytical precision is good. In brief, the spread of results depicted in Table G-4 is fairly typical. Nevertheless, the relative precision and accuracies do enable trends to be observed.

The actual amounts of the various elements listed in Table G-3 are hardly remarkable except in the case of As, which is fairly high. However, some interesting trends are observed. Most notable is the apparent variation of several elements with variations in the dRDF:coal ratio. Thus, Br, Mn, Pb, and Sb show a tendency to increase in concentration with increasing dRDF levels whereas As, Ni, and V show an opposite tendency. The trends are hardly definitive but are probably real as indicated by similar trends observed in these materials in the fly ash leachates.

Variations of concentration with particle size are also not well defined. There is, however, a general tendency for the elements As, Ga, Na, and Sb to increase in specific concentration with decreasing particle size. A pronounced increase in the concentration of Br and Mn in large particles is also observed.

The trends indicated above are not unexpected. Thus, one would expect elements such as Br, Mn, Pb, and Sb to be present at higher levels in dRDF than in coal, and the preferential association of As, Ni, and V with coal is acceptable. Similarly, the preference of As, Ga, Na, and Sb for small particles is to be expected since these elements are capable of being volatilized during combustion and then preferentially adsorbed onto small particles. The behavior of Br and Mn is not understood, however.

To investigate the association of different elements with individual particles, the size fraction S4 was subjected to energy dispersive X-ray emission analysis under a scanning electron microscope. A number of individual particles were analyzed and found to contain Al, Ca, Fe, K, Si, Ti, and Zn as consistent matrix elements (note: these are the only analyses for Fe and Zn). The presence of As, Na, P, and S was indicated in some particles, but signal intensities were too weak for absolute identification.

MECHANISM OF TRACE ELEMENT DISTRIBUTION IN FLY ASH FROM FUEL BLENDS

It has now been reasonably established that certain of the more volatile trace elements (or the compounds in which they are present) are volatilized at temperatures encountered during many combustion processes. The resulting vapor-phase metallic species then either condense or adsorb (probably the former) onto the surface of co-entrained fly ash particles as both vapor and particles move away from the high temperature combustion zone. This process results in the preferential redistribution of volatilizable species into small particles due to the fact that small particles have a larger specific surface area than large particles.

This volatilization-condensation phenomenon has several undesirable environmental consequences. First, it results in many of the more toxic elements becoming preferentially associated with small particles which are most readily emitted from most combustion operations, which can have long atmospheric lifetimes, and which are preferentially deposited in the pulmonary region of the human lung when inhaled. Secondly, the condensation phenomenon results in the presentation of toxic species on the surface of particulate matter, thereby making it most readily available to the external environment (for example, extracting body fluids). Because of these effects, it is of considerable interest to determine the extent to which such a volatilization condensation mechanism may operate. Consequently, it is appropriate to determine trends in elemental concentrations with particle size.

The dependence of elemental concentration on particle size is indicated in Table G-3. While there is some evidence that certain elements (e.g., As, Ga, Na, and Sb) increase in specific concentration with decreasing particle size (i.e., increasing particle specific surface area), these trends are not sufficiently convincing to establish the existence of a volatilization-condensation process.

To obtain direct information on surface concentrations, a number of particles were examined using auger electron spectroscopy. Since the analytical volume for this technique extends only about 10 to 20 Å below the particle surface, the spectra obtained are derived entirely from surface associated material. In order to obtain depth profiles, inner layers of the particles are exposed by etching into the particles using a stream of positively charged argon ions.

A representative scan from the auger spectrometer is presented in Figure G-5 for the S4 size fraction derived from 100 percent dRDF. This shows that the elements Al, C, Ca, Fe, P, S, Si, and Ti are the predominant surface constituents of these particles. Depth profiles for the most readily identifiable elements associated with samples derived from 0, 50, and 100 percent dRDF:coal blends are presented in Figures G-6 through G-8. Precise depth scales were not established; however, a sputtering rate of approximately 30 Å/minute was employed.

These depth profiles do not show any pronounced surface predominance for the elements observed. There is an indication that S and Si may be surface enriched and C surface depleted in some samples; however, these results could well be artifactual in the case of S and Si. Although not shown in Figures G-5 through G-8, there appears to be an increase in the weak Fe and Ti signals with depth. Chlorine, though observed initially, is rapidly removed by the electron beam.

It can be concluded that these surface studies provide no evidence for the occurrence of a volatilization-condensation mechanism. This does not mean that such a mechanism does not exist but simply that it does not apply for the elements observed by auger electron spectroscopy.

MOBILIZATION OF TRACE ELEMENTS IN SOLUTION

While the elemental composition of fly ash from dRDF:coal fuel blends was the primary measurement required in the present study, it is important to establish the extent to which the species present can be mobilized in solution. This is because the toxic trace elements exert an adverse environmental impact only if they can be transferred from the solid material to a liquid solution.

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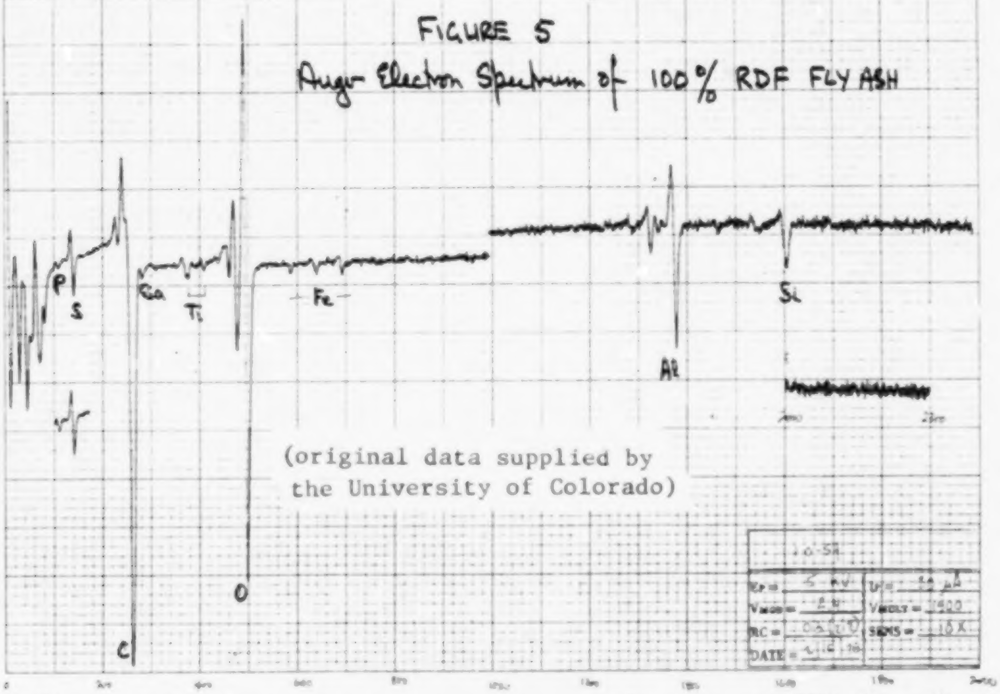

FIGURE 5

Auger Electron Spectrum of 100% RDF FLY ASH

(original data supplied by the University of Colorado)

Figure G-5. Auger electron spectrum of 100 percent dRDF fly ash.

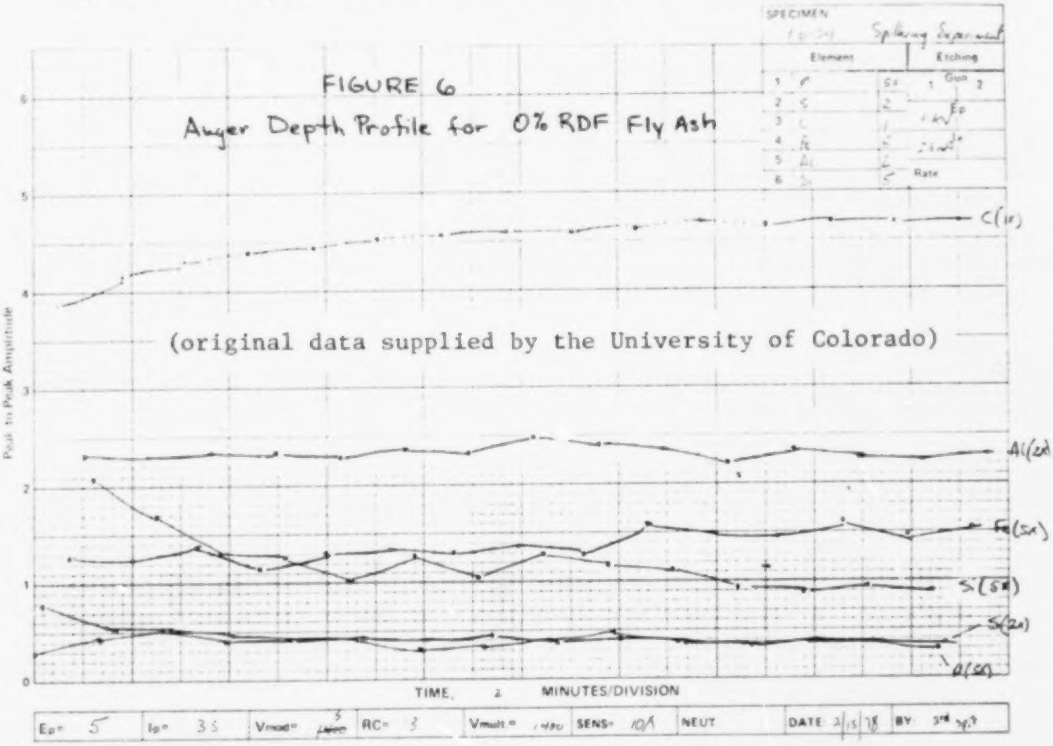

FIGURE 6

Auger Depth Profile for 0% RDF Fly Ash

(original data supplied by the University of Colorado)

Figure G-6. Auger depth profile for 0 percent dRDF fly ash.

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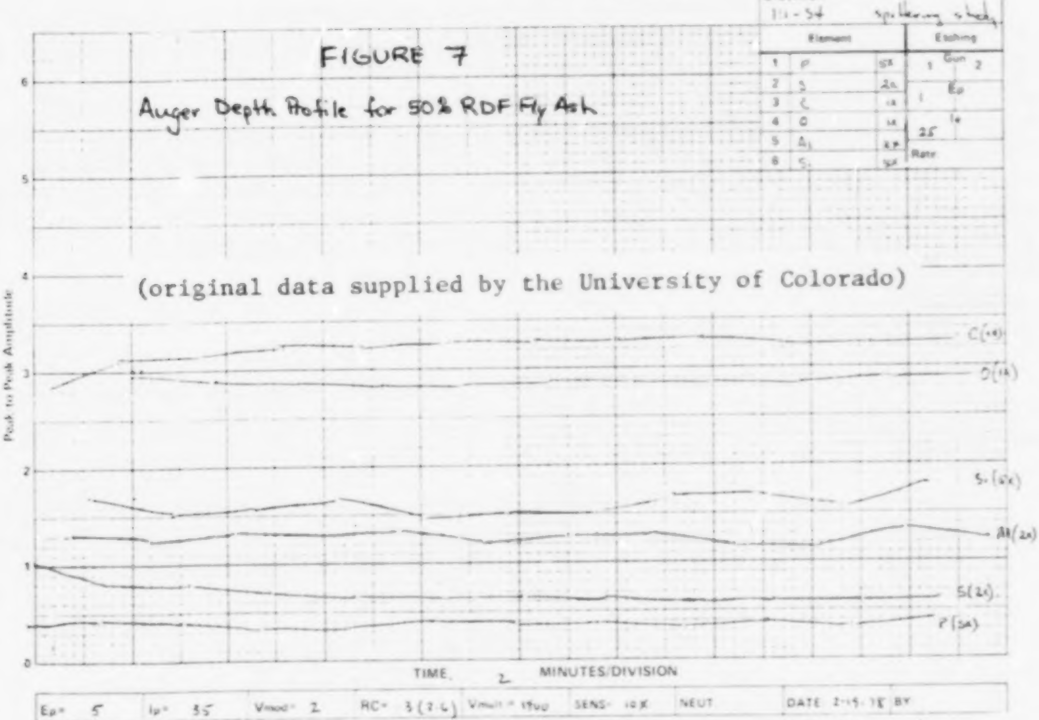
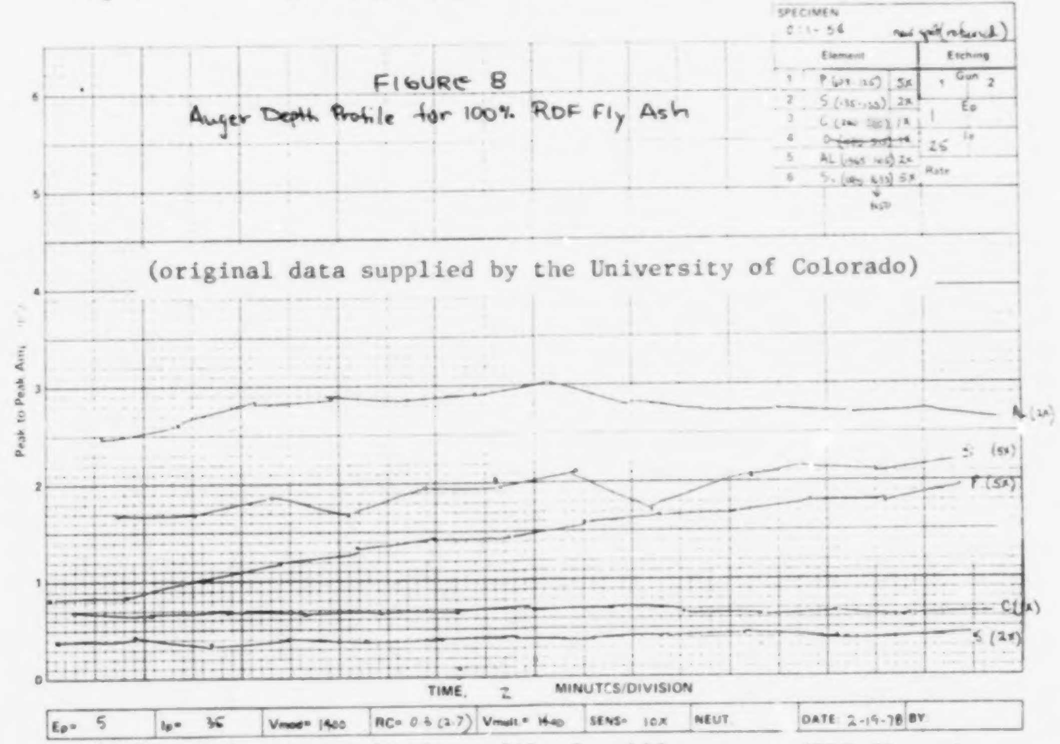


SPECIMEN
1:1-54 sputtering study

Element			Etching
1	P	5x	Gun 1 2
2	S	2x	1 Ep
3	C	1x	
4	O	1x	25 Ip
5	Al	2x	Rate
6	Si	5x	

Ep= 5	Ip= 35	Vmod= 2	RC= 3 (2.6)	Vmult = 1900	SENS= 10x	NEUT	DATE 2-15-78	BY

Figure G-7. Auger depth profile for 50 percent dRDF fly ash.



SPECIMEN
0:1-56 [illegible]

Element			Etching
1	P (120-125)	5x	Gun 1 2
2	S (135-155)	2x	1 Ep
3	C (240-285)	1x	
4	~~O (492-512)~~	~~1x~~	25 Ip
5	AL (1365-1415)	2x	Rate
6	Si (1605-1635)	5x	

Ep= 5	Ip= 36	Vmod= 1400	RC= 0.3 (2.7)	Vmult = 1400	SENS= 10x	NEUT	DATE 2-19-78	BY

Figure G-8. Auger depth profile for 100 percent dRDF fly ash.

In order to obtain information about the solubility characteristics of the fly ash, the size fractions S3 through S7 were ultrasonically agitated (Heat Systems Model W 200R Sonicator Cell Disruptor) for 2 hours with 15 mls of triply distilled water. Sample masses varied from 0.0019 to 0.0230 g. (Previous studies have established that water soluble material can be quantitatively extracted under these conditions.) Following sonication, the samples were filtered through a 0.45-μm millipore filter. Elementa analyses of the filtrate were then performed using plasma emission spectrometry, and anion analyses were performed by ion chromatography using a Dionex Model 10 ion chromatograph. A representative ion chromatogram showing the presence of fluoride, chloride, nitrate, and sulfate in the leachate from the fly ash is presented in Figure G-9.

The results obtained from these analyses are presented in Table G-4. Correction has been made for all blank levels and precision is generally $\leq$10 percent.

These solubility studies provide considerable information about both the chemical characteristics and the potential environmental impact of the fly ash. Thus, with reference to the data in Table G-4, a number of trends can be observed.

First, it is apparent that for most species the amount of material which is soluble increases with increasing RDF levels in the original fuel blend. This trend can be seen clearly for Ca, Cu, K, Mg, Mo, Na, Pb, Si, Cl^-, NO_3^-, and SO_4^{2-} and may occur for B, Ba, Cd, and F^-. A reverse trend is observed for Ni and P and, possibly, for Cr and Sr. The fact that many of the major matrix elements exhibit increasing solubility with increasing dRDF percentage indicates that the addition of dRDF to coal will result in greater bulk solubility (as well as greater trace element mobilization) as compared with pure coal fly ash.

The second obvious trend is towards increasing mobilization of species with decreasing particle size. This is apparent for Cd, Cr, Cu, K, Mn, Mo, Na, Ni, Pb, and Cl^- and may occur for Ba, Be, P, and F^-. This trend may be due to condensation of these species from the vapor phase as discussed earlier, or it may result from the more efficient formation of soluble oxides (i.e., calcining) in small particles. In the former case one would expect to see similar size dependenices for both the bulk (Table G-3) and the separated soluble sample (Table G-4). This would not be the case if solubility is the direct result of chemical reaction at a particle surface. Unfortunately, the available data are not sufficient to rule out either mechanism.

Further consideration of the data in Tables G-3 and G-4 provides some interesting insights into the fractional solubility of fly ash from dRDF:coal blends. As an initial general statement, it can be said that matrix elements such as Al, Ba, Mg, P, Si, and Sr exhibit quite low solubility ($\leq$10 percent) whereas minor and trace elements such as Be, Cd, K, Mn, and Na are fairly soluble (approximately 20 to 80 percent). Calcium is a notable exception to this rule insofar as it exhibits high solubility. In considering this

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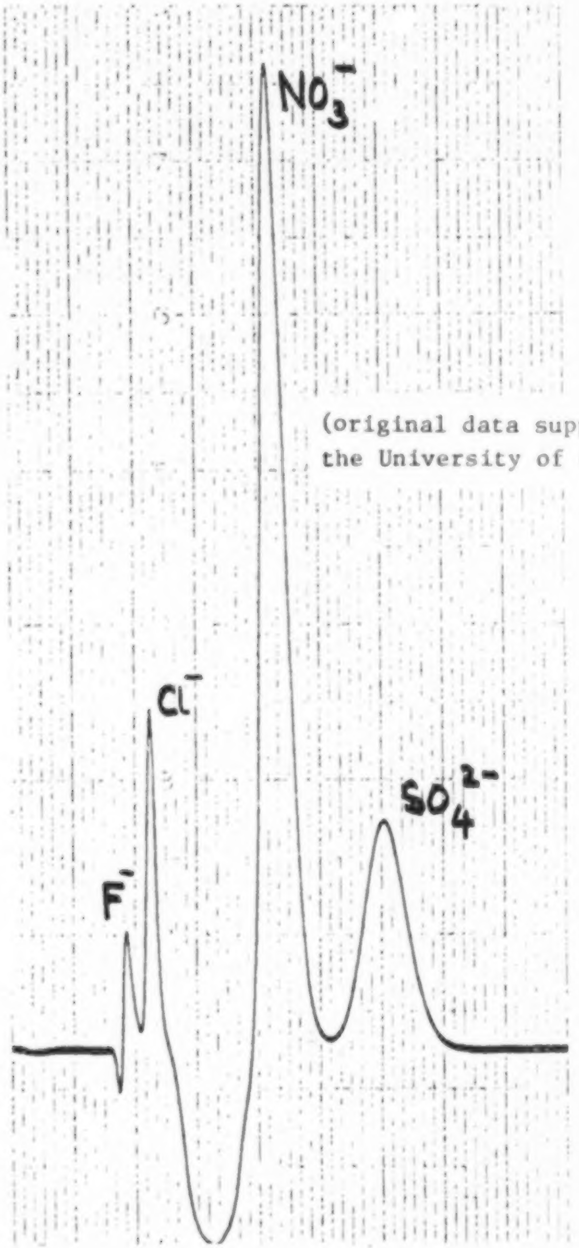

(original data supplied by the University of Colorado)

(2:10 dilution, 0-3 micromhos full scale deflection)

Figure G-9. A representative Ion Chromatograph of Sample: 1-0-S7.

TABLE G-4. CONCENTRATIONS OF SEVERAL METALLIC ELEMENTS AND ANIONS IN AQUEOUS LEACHATES FROM dRDF:COAL FLY ASH (μg/g of fly ash leachate)

		dRDF Fuel Blend Composition			
Element	Size	0% dRDF by volume	50% dRDF by volume	67% dRDF by volume	100% dRDF by volume
Aluminum					
	S3	18.8	2.12	6.15	31.3
	S4	138	12	8.40	112
	S5	148	3.90	--	194
	S6	24.6	263	--	181
	S7	3.03	158	--	<10.1
Barium					
	S3	3.02	2.74	3.93	3.57
	S4	17.2	25.8	11.0	61.0
	S5	42.3	44.2	--	169
	S6	13.9	68.4	--	171
	S7	<12.3	77.5	--	35.9
Beryllium					
	S3	0.123	<0.342	<0.427	<0.714
	S4	<2.61	<5.00	<4.70	<4.86
	S5	2.01	<1.31	--	<2.81
	S6	2.46	<5.32	--	4.76
	S7	9.09	2.50	--	1.71
Boron					
	S3	<1.62	<1.79	<2.24	<3.74
	S4	20.4	25.5	32.2	56.5
	S5	22.1	77.9	--	22.2
	S6	12.3	<346	--	<313
	S7	<199	<165	--	<56.2

(continued)

TABLE G-4 (continued)

Element	Size	dRDF Fuel Blend Composition 0% dRDF by Volume	50% dRDF by Volume	67% dRDF by Volume	100% dRDF by Volume
Cadmium					
	S3	1.17	<0.189	<0.236	<0.395
	S4	<7.20	<13.9	<13.0	<13.4
	S5	<12.8	<24.8		<53.0
	S6	<15.6	<100		252
	S7	<167	120		527
Calcium					
	S3	343	620	769	1,680
	S4	750	2,300	2,370	7,750
	S5	1,140	3,020	--	16,700
	S6	862	2,550	--	8,490
	S7	830	548	--	899
Chloride					
	S3	<560	223	72.6	2,310
	S4	<137	56.9	792	6,310
	S5	<346	<669	--	13,000
	S6	28.7	<2,710	--	33,700
	S7	417	<1,290	--	54,900
Chromium					
	S3	0.926	0.822	0.684	1.71
	S4	<1.16	<2.24	<2.09	<2.16
	S5	6.04	5.19	--	<11.2
	S6	5.74	<21.3	--	28.6
	S7	33.3	10.0	--	6.84

(continued)

TABLE G-4 (continued)

Element	Size	dRDF Fuel Blend Composition			
		0% dRDF by Volume	50% dRDF by Volume	67% dRDF by Volume	100% dRDF by Volume
Copper					
	S3	<0.926	0.274	0.684	<3.14
	S4	2.33	<5.50	<5.15	<5.35
	S5	<3.39	<6.56	--	<14.0
	S6	<4.14	5.26	--	76.2
	S7	27.3	228	--	292
Fluoride					
	S3	<443	<491	72.6	275
	S4	12.6	27.8	792	221
	S5	<72.8	<141	--	49.3
	S6	28.5	<1,140	--	2,130
	S7	107	<271	--	<92.7
Lead					
	S3	<5.04	3.70	4.79	7.71
	S4	<1.04	15.5	6.10	12.0
	S5	18.1	22.1	--	283
	S6	13.9	1,740	--	2,420
	S7	60.6	7,890	--	4,720
Magnesium					
	S3	33.1	18.1	25.1	94.6
	S4	178	308	350	328
	S5	310	474	--	1,240
	S6	281	353	--	1,300
	S7	248	70.0	--	100

(continued)

TABLE G-4 (continued)

Element	Size	dRDF Fuel Blend Composition 0% dRDF by Volume	 50% dRDF by Volume	 67% dRDF by Volume	 100% dRDF by Volume
Manganese					
	S3	2.22	4.79	5.47	2.43
	S4	10.6	29.0	25.2	4.00
	S5	26.8	36.4	--	74.0
	S6	25.4	26.3	--	119
	S7	57.6	30.0	--	36.8
Moybydenum					
	S3	0.864	1.03	1.11	4.14
	S4	2.15	<2.14	2.90	9.00
	S5	14.8	9.09	--	27.8
	S6	24.6	<37.5	--	42.9
	S7	60.6	2.50	--	8.55
Nickel					
	S3	0.556	0.822	3.08	1.57
	S4	5.40	5.15	2.26	<0.665
	S5	17.4	6.49	--	<33.8
	S6	17.2	10.5	--	9.52
	S7	24.2	70.0	--	1.71
Nitrate					
	S3	60,000	142,000	199,000	207,000
	S4	1,550	2,160	1,980	2,620
	S5	1.580	7,690	--	<21,500
	S6	6,090	10,400	--	29,800
	S7	5,380	<19,400	--	8,890

(continued)

TABLE G-4 (continued)

Element	Size	dRDF Fuel Blend Composition 0% dRDF by Volume	50% dRDF by Volume	67% dRDF by Volume	100% dRDF by Volume
Phosphorous					
	S3	<31.0	<34.4	<11.7	18.9
	S4	46.6	40.7	34.2	4.66
	S5	205	18.2	--	142
	S6	101	<1,450	--	890
	S7	870	27.5	--	200
Potassium					
	S3	257	525	160	630
	S4	870	1,200	835	2,260
	S5	1,460	2,710	--	11,100
	S6	1,480	7,950	--	24,000
	S7	1,280	15,400	--	38,000
Silicon					
	S3	25.2	15.0	38.6	163
	S4	105	129	186	325
	S5	170	184	--	1,120
	S6	161	21.1	--	948
	S7	288	<200	--	212
Sodium					
	S3	444	514	1,050	1,920
	S4	545	3,340	3,120	6,700
	S5	584	7,900	--	29,200
	S6	295	18,100	--	63,600
	S7	<3,280	32,600	--	82,400

(continued)

TABLE G-4 (concluded)

Element	Size	dRDF Fuel Blend Composition 0% dRDF by Volume	50% dRDF by Volume	67% dRDF by Volume	100% dRDF by Volume
Strontium					
	S3	4.75	7.53	5.47	10.1
	S4	34.8	49.6	25.8	40.0
	S5	72.5	70.1	--	80.6
	S6	32.8	42.1	--	19.0
	S7	130	<25.3	--	3.42
Sulfate					
	S3	43,100	82,500	80,800	110,000
	S4	10,800	17,900	17,700	25,400
	S5	11,600	23,800	--	40,800
	S6	11,900	56,800	--	66,200
	S7	8,640	107,500	--	75,000

fractional solubility, it is noteworthy that there is a trend of increasing fractional solubility with decreasing particle size for several elements, the most notable of which is Mn. Since Mn exhibits no dependence of concentration on particle size in Table G-3, one can tentatively conclude that, for this element at least, its solubility increase with decreasing particle size is simply due to the more efficient calcining, and thus the greater bulk solubility, of small particles.

CONCLUSIONS

The following tentative conclusions can be drawn:

1. The specific concentrations of trace elements present in the fly ash from blend combustion are quite similar to those found in pure coal fly ash. The dRDF seems to be the main contributor of Br, Mn, Pb, and Sb in this particular case while the coal is the primary source of As, Ni, and V.

2. There is a tendency for several elements to be preferentially concentrated in small particles, notably As, Ga, Na, and Sb.

3. It is apparent that the volatilization-condensation mechanism which is responsible for partitioning volatile elements into small fly ash particles in a coal-fired power plant is less effective in the plant used to burn the dRDF:coal blend. This is probably due to the lower temperatures achieved in the blend combustion since the most volatile elements still exhibit volatilization-condensation partitioning.

4. The solubility of the fly ash increases with increasing dRDF content.

5. The solubility of both trace and matrix species present in small particles is significantly greater than in large particles.

The overall conclusion to be drawn is that utilization of dRDF supplements to coal for energy generation will generally increase the amounts, mobility, and toxic potential of inorganic species associated with the emitted fly ash as compared with that associated with pure coal fly ash.

APPENDIX H

PRECEDING COAL:dRDF BLEND STUDIES

INTRODUCTION

In recent years European and American industries and government agencies have become increasingly interested in the commercial conversion of urban solid waste into a stoker coal substitute. Since little of the European research data are available, this appendix is limited to the American developments.

The following synopses of American tests conducted between 1972 and 1976 represent all information that could be gathered on these tests. While the data in these synopses are incomplete, they give a qualitative and quantitative insight into the recent developments.

FORT WAYNE MUNICIPAL ELECTRIC STATION TESTS[1]

The municipal electric station in Fort Wayne, Indiana, conducted these tests with RDF cubettes supplied by the National Recycling Corporation (NRC) of the same city.

Fuel Preparation System

As shown in the flow diagram of Figure H-1, NRC prepared the cubettes from paper and paper board scraps collected from local paper mills. The NRC plant includes a modified John Deere stationary alfalfa cubetter which has a nominal capacity of 4.6 to 9.1 Mg/hr (5 to 10 TPH). This capacity varies with the relative density of the scraps being densified. Up to 20 TPH of waste can be injected into the cubetter and processed into fuel. White metals, yellow metals, glass, and ceramics were excluded from the cubettes since their low softening temperatures would likely cause clinkering and make the furnace ash handling difficult. The cubettes were approximately 1-1/2 × 1-1/2 × 2 in. and were free of metals and glass. Occasionally moisture was added to improve the binding qualities of the scrap waste.

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[1] Hollander, H. I. and N. F. Cunningham, "Beneficated Solid Waste Cubettes as Salvage Fuel for Steam Generation," Proceedings 1968 National Incinerator Conference, ASME, pp. 75-86.

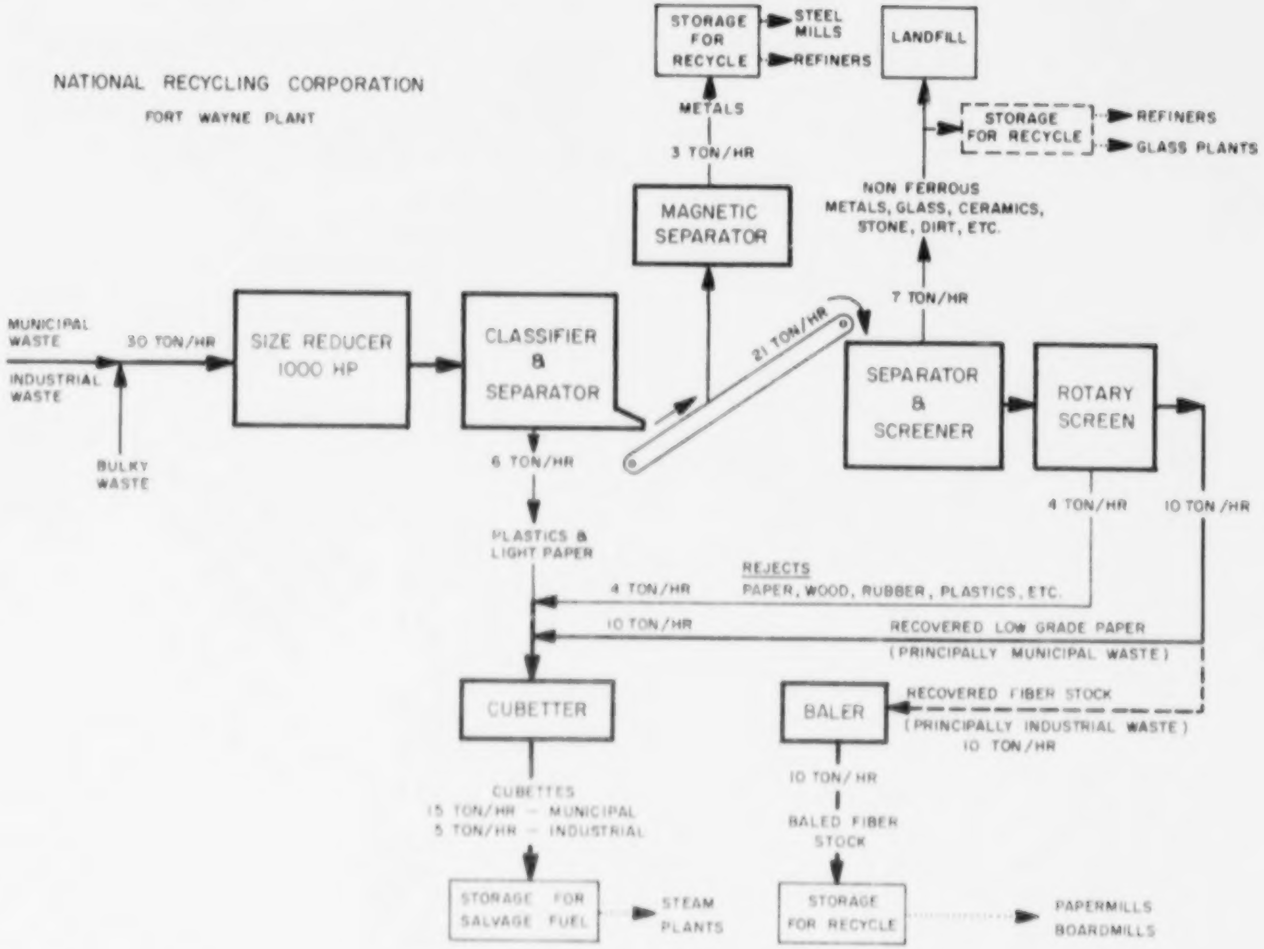
NATIONAL RECYCLING CORPORATION
FORT WAYNE PLANT
MUNICIPAL WASTE
INDUSTRIAL WASTE
BULKY WASTE
30 TON/HR
SIZE REDUCER 1000 HP
CLASSIFIER & SEPARATOR
6 TON/HR
PLASTICS & LIGHT PAPER
21 TON/HR
MAGNETIC SEPARATOR
3 TON/HR
METALS
STORAGE FOR RECYCLE
STEEL MILLS
REFINERS
SEPARATOR & SCREENER
7 TON/HR
NON FERROUS METALS, GLASS, CERAMICS, STONE, DIRT, ETC.
LANDFILL
STORAGE FOR RECYCLE
REFINERS
GLASS PLANTS
ROTARY SCREEN
4 TON/HR
10 TON/HR
REJECTS
PAPER, WOOD, RUBBER, PLASTICS, ETC.
4 TON/HR
10 TON/HR
RECOVERED LOW GRADE PAPER
(PRINCIPALLY MUNICIPAL WASTE)
RECOVERED FIBER STOCK
(PRINCIPALLY INDUSTRIAL WASTE)
10 TON/HR
CUBETTER
CUBETTES
15 TON/HR — MUNICIPAL
5 TON/HR — INDUSTRIAL
STORAGE FOR SALVAGE FUEL
STEAM PLANTS
BALER
10 TON/HR
BALED FIBER STOCK
STORAGE FOR RECYCLE
PAPERMILLS
BOARDMILLS

Figure H-1. Flow chart and mass balance for cubette production at the National Recycling Corporation.

Furnace and Boiler Facility

The tests were performed in one of the four furnace-boiler units. Each unit includes a multiple retort, an underfed retort stoker-fired furnace with a Sterling boiler, an economizer, and an air preheater. The boilers produce 2654 kPag (385 psig), 371°C (700°F) steam to drive turbine generators which have a combined capacity of 40 megawatts. None of the plant equipment had to be modified to accommodate the tests.

Test Program

Approximately 36 Mg of cubettes were burned during two tests. A fuel analysis revealed that the Btu content of the as-received cubettes ranged from 15.9 to 19.8 MJ/kg (6850 to 8530 Btu/lb). The average fuel properties are shown in Table H-1. The tests were run at a 3:1 (coal:cubette) ratio. While the cubette firing improved the appearance of the fuel bed, the smoke opacity remained the same as when firing coal only. Although the tests were successful, no further cubette firing has been reported.

TABLE H-1. ANALYSIS OF FUEL BURNED IN FORT WAYNE TESTS

Characteristic	Content
Moisture	15%
Volatile Matter	65%
Fixed Carbon	14%
Ash	6%
HHV as Fired	6800 Btu/lb (15.8 MJ/kg)
Sulfur	0.25%
Chlorine	0.20%
Hemispheric Reducing Atmosphere Temperature	1148°C

SUNBURY STEAM ELECTRIC STATION TESTS[2]

The Sunbury Steam Electric Station of the Pennsylvania Power and Light Company conducted these tests with pellets prepared by Elo & Rhodes in Easton, Pennsylvania.

Fuel Preparation System

Elo & Rhodes had ground mixed municipal solid waste to less than 2.5 cm, pelletized the ground particles, and then delivered the pellets to a storage bin. According to the fuel property summaries in Tables H-2 and H-3, the waste benefication reduced the ash level to 20.6 percent and the moisture to 10.3 percent. The high heating value of the pellets is suspect because on a moisture and ash-free basis, the heating value for the Elo & Rhodes pellets is 22.6 MJ/kg (9700 Btu/lb) while the value for the NCRR pellets is 21.2 MJ/kg (9100 Btu/lb).

Furnace and Boiler Facility

The test boiler at the Sunbury plant was the No. 4 boiler which is equipped with three ball-in-tube mills that are normally used for pulverizing coal. While a Raymond Bowlmill was acquired for the pellet pulverizing, the ball-in-tube mills had to be used since the bowl mill did not perform satisfactorily. The maximum generator capacity under normal conditions was 140 Mw, but only 10 of the 12 burners were operable, and the boiler ratings could not be attained. The pellets were nominally 5/8 in. in diameter and 1 in. long.

Test Program

Forty tons of pellets were burned during the test. It was difficult to unload the pellets from the hopper cars because they had packed and bridged over the bottom of the sliding gates on the cars. The pellet handling produced excessive dust in the plant.

As the firing of the coal-pellet blend stabilized, the boiler output decreased from the 120 Mw with coal-only firing to 104 Mw with the blend firing. This drop was due to the lesser pulverizer capacity that reduced the fuel input to the boiler. The pellets were fired for 6 1/2 hours. Although the exact mixture of pellets and coal was not determined, it was estimated that the pellets accounted for 45 percent of the total heat input. Table H-4 summarizes the monitored gaseous stack emissions. While the SO_3 concentration doubled, the total SO_2 concentration remained the same. The chlorides increased as expected. In general, the tests were successful. However, the Sunbury staff has not indicated any interest in continuing the pellet firing.

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[2] Author-unknown, "Final Report on Burning of Processed Refuse Pellets in No. 4 Steam Generator on May 29 and 30, 1975" Sunbury Steam Electric Station report, undated, 9 pages.

TABLE H-2. ANALYSIS OF FUEL BURNED IN SUNBURY TESTS

As Received		Processed Refuse*	Bituminous to Mills
Proximate Analysis			
Moisture	%	10.3	4.7
Ash	%	20.6	16.0
Volatile Matter	%	51.8	26.2
Sulfur	%	0.4	3.1
Heating Value	Btu/lb	6,680	12,011
	Mj/kg	15.5	27.9
Ultimate Analysis			
Nitrogen	%	0.74	0
Hydrogen	%	5.16	4.16
Carbon	%	39.42	65.81
Oxygen	%	31.18	11.10
Ash	%	23.00	14.90
Sulfur	%	0.50	4.03

* Average of two samples

TABLE H-3. PARTIAL ANALYSIS OF ASH IN SUNBURY TESTS

		Refuse	Bituminous
Silicon Dioxide	%	41.94	36.96
Aluminum	%	6.77	8.19
Iron and Titanium	%	4.89	23.48
Calcium	%	6.95	0.66
Magnesium	%	1.86	0.61
Sodium	%	3.24	0.39
Potassium	%	2.14	1.50
Chlorides	%	0.04	trace
Remainder	%	32.17	28.21
		100.00	100.00

TABLE H-4. FLUE GAS ANALYSIS AFTER THE INDUCED DRAFT FAN AT SUNBURY

Date	Time		SO_3 ppm	SO_2 ppm	CL ppm
5/29/75	8:00 AM 10:00 AM	Baseline	9.3	935	0
5/29/75	11:20 AM 1:00 PM	1	18.7	994	6 & 6
5/29/75	2:00 PM 4:00 PM	2	18.5	1008	8 & 11

PIQUA, OHIO, BLACK-CLAWSON TESTS[3]

These tests with coal-pellet firings were conducted by Black-Clawson Fibreclaim, Inc., at the Piqua Municipal Power Plant.

Fuel Preparation System

The Black-Clawson Fibreclaim Company in Franklin, Ohio, prepared 22 tons of nominal 3/8-in.-diameter pellets for the Piqua plant tests. They trucked wet fiber that had been produced in their solid waste processing plant to the Toledo Alfalfa Company, Middletown, Ohio, where the fiber was dried in a Heil Model 125 triple-pass rotary dryer. Upon the return of the fiber to Franklin, Black-Clawson produced the pellets in a California Century pelletizer mill. A composite sample of the pellets had the fuel properties listed in Table H-5.

Boiler and Furnace Facility

Boiler No. 4 in the Piqua Municipal Power Plant was used for the test. Manufactured in 1947 by the Combustion Engineering Company, this boiler has a rating of 18.9 kg/sec (150,000 lb/hr). Normally, the maximum steam pressure is 3130 kPag (454 psig) at 440°C (750°F). The stoker is a Lloyd/Combustion Engineeering chain grate. The economizer was designed and built by Combustion Engineering. The air preheater was rated at a 2.7 GJ/hr (2.6 MMBtu/hr) input. Emission control devices were not installed in this facility.

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[3] Marsh, Paul, Black-Clawson Fibreclaim, Inc., "Preliminary Test Report on Handling and Combustion Characteristics of Franklin Pelletized Fuel and Coal Mixes," November, 1975, 17 pages.

TABLE H-5. CHARACTERISTICS OF THE PIQUA dRDF

Moisture	%	16.5
Ash	%	9.02
Volatile	%	63.7
Fixed Carbon	%	10.38
Sulfur	%	0.22
Heating Value	Btu/lb	6382
	MJ/kg	14.8

Test Program

The 20 Mg (22 tons) of pellets were mixed with an equal volume of coal by a bulldozer in the coal yard. The mixture was then pushed with a front-end loader into the bucket elevator and then transported by a drag chain conveyor to the overhead bunkers from which it was metered to the grate through a weigh lorry. No modifications were made to the existing coal handling system. There were no mechanical problems during the test. Except for the normal airflow and bed-depth adjustments for a particular fuel, the boiler operated as for coal-only firing.

The blend was approximately 1:1 by volume, and the pellet substitution provided 20 to 24 percent of the heat generated. The steam pressure and temperature were maintained during a 7-hr test. The plant's normal coal analysis is shown in Table H-6.

Conclusions

The 1:1 tests demonstrated the feasibility of using dRDF as a coal supplement. Additional tests with a 2:1 mix, along with a detailed combustion and emission assessment, were judged desirable.

TABLE H-6. ANALYSIS OF THE COAL CO-FIRED IN PIQUA, OHIO

Parameter	As Received	Dry Basis
Moisture Percent	4	
Volatile Matter Percent	37.51	39.07
Fixed Carbon Percent	46.70	48.65
Ash Percent	11.79	12.28
Sulfur Percent	3.36	3.50
Btu/lb	11,680	12,170
MJ/kg	27.2	28.3
Ash from the coal		
Initial Deformation Temperature	1263°C, 2306°F	
Second Softening Temperature	1318°C, 2405°F	
Fluid Temperature	1471°C, 2680°F	

WRIGHT-PATTERSON AFB BLACK-CLAWSON TESTS[4]

These tests were conducted by Black-Clawson Fibreclaim, Inc., at the Wright-Patterson Air Force Base central heating plant, Building 770.

Fuel Preparation System

As for the Piqua Tests, Black-Clawson similarly prepared pellets for the Wright Patterson AFB tests. Typical properties of the latter pellets are listed in Table H-7.

Furnace and Boiler Facility

The central heating plant contains two Edgemoor Ironworks (36,300 kg/hr) (80,000 lb/hr) boilers that produce 862 kPag (125 psig) of saturated steam. Installed in 1956, these boilers are fired with Detroit Rotograte spreader stokers. The emission control equipment includes a cyclone separator for reinjected fly ash, multiclones for coarse particulate control, and an installed, but inoperative, electrostatic precipitator.

Test Program

The pellets trucked to Wright-Patterson AFB were placed in hopper cars for delivery to the rail car dumper and then into the power plant hoppers.

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[4] Jackson, J. W., "A Bioengineering Study of Emissions from RDF," UASFEHL, McClellan AFB, ADA024661, 1976.

TABLE H-7. PROPERTIES OF THE dRDF AND STOCK USED IN THE WPAFB TEST

	Feed Stock As Received	dRDF As Received
Energy - Btu/lb	3300	5800
MJ/kg	7.6	13.5
Moisture Percent	55.5	21.5
Ash Percent	6.2	11.2
Chloride Percent	0.07	
Sodium	0.03	
Softening Temperature	1266°C (2310°F)	
Density Kg/m^3	46	58.2
Sulfur Percent		0.12
Volatile Percent		60.2
Fixed Carbon		10.46

Two methods of mixing the pellets with coal were used to investigate the mixing behavior. In the first method, a pile of blended fuel was prepared in the coal yard by having a car unloading crane first alternately scoop and deposit dRDF and coal and then lift and drop the deposit for further mixing. The mixture was then loaded into a hopper car and delivered to the coal bunker. In the second method, alternate scoops of the two fuels were simply loaded into the hopper car with the fuels being mixed as they were unloaded from the car and passed through the materials handling system to the coal bunker. Both methods produced a visibly well-mixed fuel. After the blends were loaded onto the coal cars, they were covered to prevent rain from reducing them to their original pulped form. Calculated blend properties are presented in Table H-8.

Two blend ratios were burned: 1:1 (coal:dRDF) by volume for 34 hours and 1:2 by volume for 6 hours. Although the emissions were monitored, they were uncontrolled since the installed electrostatic precipitator had been inoperative for several years.

As indicated by the summary of the stack emissions in Table H-9, the results were encouraging.

In contrast to the Sunbury tests, SO_2 was reduced in the Wright-Patterson AFB tests. Moreover, the unburned hydrocarbons were drastically reduced in the latter tests. Halides and heavy metal emission test data, however, could not be interpreted conclusively, although increases were detected.

TABLE H-8. AVERAGE PROPERTIES OF WPAFB dRDF

Properties	Coal	1:1 Mix	2:1 Mix
Heating Value MJ/kg	30.0	26.3	22.1
(As Fired) Btu/lb	12,900	11,327	9,518
Moisture Percent	4.88	7.73	14.01
Bulk Density lb/CF	53.1	44.2	42.4
kg/m^3	851	708	679
Ash Percent	7.5	9.09	8.86
Sulfur Percent	0.67	0.53	0.43
Chlorine Percent	0.09	0.14	0.14
Fixed Carbon Percent	55.6	43.8	36.5
Volatiles Percent	31.9	39.3	40.6
Hydrogens Percent	4.9	5.09	4.91
Carbon Percent	73.3	63.5	56.5

TABLE H-9. STACK EMISSIONS (COMPARED TO COAL)

Emissions	1:1 Mix	1:2 Mix
Particulates	Unchanged	Highly variable, on the average, unchanged
SO_2	Reduced by approximately 50%	Reduced by approximately 60%
NO_x	Drastically reduced by approximately 80%	Drastically reduced by 95+ %

The boiler operation was normal during the 1:1 mix test after a few minor control adjustments. However, during the 1:2 mix test, a loss of control over the fuel distribution in the boiler caused the fire to concentrate near the rear of the firebox. In the automatic scale operation, some fuel segregation produced a higher concentration of pellets in the middle spreaders. Clinkers formed near the heavy fire concentration at the rear of the boiler. The bottom ashes produced by the 1:1 blend firing differed little from the bottom ashes produced by the coal-only firing. With the 2:1 mix, however, the ashes were frequently fused into clinkers.

A furnace inspection after the test revealed that some slag had deposited on the rear wall refractory and on the rear portions of the side walls. These deposits may have been caused by the poor fuel distribution during the 1:2 blend tests. Small slag cones which had formed at the base of the slag deposit indicated that ash had melted. Another evidence of fouling was the formation of flake-like deposits on the fire side of the wall tubes. These deposits generally sloughed off the tubes when the boiler cooled. After the grates were swept clean, black stains were found with those close to the grate air holes being the most prominent.

Conclusions

While the 1:1 mixture firing was generally satisfactory, the 2:1 mixture firing caused poor fuel distributions which likely could have been solved by minor facility modifications. A larger and more dense pellet should be tested since its handling characteristics might solve some of the fuel distribution deficiencies at the higher coal:RDF ratio. The potential for scaling and waste should be evaluated further. The stack emission changes were generally acceptable, and the decrease in hydrocarbons was especially noteworthy. Lead emissions, which increased significantly during the tests, were generally submicron aerosols that indicated the deposition of lead vapors. The NO_x and chloride-fluoride emissions in both the 1:1 and the 2:1 blend tests were significantly greater than those in the coal-only firings.

SANDWELL INTERNATIONAL TESTS[5]

These tests with fluff and densified RDF firings were conducted by Sandwell International, Inc., at a facility owned by the Eugene Water & Electric Board, Eugene, Oregon.

Fuel Preparation System

The Vista Fiber and Chemical Company in Los Gatos, California, produced 21 tons of nominal 1-in.-diameter dRDF pellets for these tests. The material density of the individual pellets was 881 kg/m^3 (55 lb/ft^3), and the bulk density was approximately 593 kg/m^3 (34 lb/ft^3). The average calorific value of the fuel was 12.0 MJ/kg (5156 Btu/lb) as received and 15.0 MJ/kg (6436 Btu/lb) on a dry basis.

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[5] Sandwell International, Inc., "Eugene Water & Electric Board, Eugene, Oregon, Solid Waste Fuel Modifications, Second Series Burn Tests--Final Report," Report W3508/2, December 23, 1974.

Boiler and Furnace Facility

The facility consists of three wood waste and bark boilers of unreported design or manufacture. Testing was done in the No. 3 boiler. This boiler has a nominal capacity of 19.5 kg/sec (155,000 lb/hr) of steam and produces 427°C (800°F) superheated steam. The boiler has an air preheater and is fired with a spreader stoker/traveling grate combination.

Test Program

The 21 tons of pellets were fed into the furnace during a 90-minute period or at a feed rate equivalent to 304 Mg/day (335 TPD). As the furnace exit gas temperatures increased from 593°C to 760°C (1100°F to 1400°F), the speed of the feeders was reduced. The steam output reached 18.9 kg/sec (150,000 lb/hr) at 1169 kPag (300 psig) and could have attained a higher output if additional fuel had been available. Although the emissions during the dRDF tests were not analyzed, the fluff RDF tests indicated that the particulate emissions, especially the fine particulate content, were generally greater than those from coal only.

WISCONSIN SOLID WASTE RECYCLING AUTHORITY TESTS[6]

Of the several dRDF tests sponsored by the Wisconsin Solid Waste Recycling Authority, three are synopsized as follows:

University of Wisconsin Tests

These tests with dRDF pellets were conducted at the University of Wisconsin heating plant. For these tests, Gruman Eco Systems in St. Louis prepared the pellets by densifying in a Sprout Waldren pelletizer the RDF produced at the municipal RDF pilot plant. The pellets were 3/4 in. in diameter and up to 3 in. long with a bulk density of 62.4 kg/m^3 (39 lb/ft^3) and a heating value of 14 MJ/kg (6000 Btu/lb). The test furnace-boiler was a Wickes waterwall furnace equipped with a Detroit Vibragrate stoker and a water tube boiler rated at 5.7 kg/sec (45,000 lb/hr) of 1862 kPag (125 psig) saturated steam. The underfire air was delivered to the grate through a 5-compartment wind box. A baffle chamber provided the means for some removal of particulate emissions.

Three volumetric coal:dRDF blends were burned during the test: 1:1, 1:3, and 0:1 (100 percent pellets). In each test, the furnace-boiler performed satisfactorily under automatic control with the facility operating between one quarter and one half of the design load. The burnout was excellent, no emissions were visible; and no clinkers were formed. Although the overfire air was not adjusted, the underfire air was throttled so that it was introduced primarily through the first zone of the 5-compartment wind box. No emissions data were collected.

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[6] Private Correspondence between Warren Porter of Wisconsin Solid Waste Recycling Authority and H. G. Rigo, 1976.

Appleton Division Tests

These tests were conducted in the boiler house of the Appleton Division. A blend of dRDF and bark was fed through a gravity feed chute into a Dutch oven-fired, refractory-walled bark burner. With the dRDF fed at a rate of 2.73 kg/hr (3 tons/hr), the furnace heat release rate rose above the design limit after 2 hours of firing, and consequently the blend feeding had to be stopped. A pile of unburned material in the middle of the furnace was high enough to block the overfire air ports and to cause poor combustion, smoking, and clinkering. However, when the test was repeated at a slightly lower feed rate, the combustion was satisfactory.

During the second test, a single stack test had particulate emission rate of 94 mg/MJ (0.219 lb/MBtu). Most of the ash in the dRDF remained in the boiler as bottom ash. There was no visible plume.

Menasha Paperboard Mill Tests

These tests were conducted in the boiler house of the Menasha Paperboard Mill. For these tests, 11.6 MJ/kg (5000 Btu/lb) dRDF prepared by the Vista Fiber and Chemical Company was blended with 31.3 MJ/kg (13,444 Btu/lb) coal in the existing fuel handling system. The coal:dRDF blend, which had a 15 percent dRDF substitution rate, was fired in a spreader stoker boiler. The plant evaporation rate decreased from 9.75 to 9.05 kg steam/kg fuel as the blend entered the boiler.

The plant power chief stated that although the blend firing appeared feasible since it required no feed equipment changes, its particulate emission was high.[7]

CHANUTE AIR FORCE BASE TESTS

The U.S. Army Construction Engineering Research Laboratory conducted these tests with pellets at Chanute Air Force Base for the Naval Facilities Engineering Command. These tests provided a unique experience since they were conducted in a chain grate stocker boiler and most of the pellets had deteriorated into fines.

Fuel Preparation System

For these tests, the Vista Fiber and Chemical Company of Los Gatos, California, prepared 181 Mg (200 tons) of dRDF pellets from mixed municipal solid waste. In this preparation, the waste was course shredded, magnetically separated, fine shredded, reshredded, air classified, screened, and pelletized in a California Pellet Mill pelletizer.

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[7] Letter to Warren Porter from C. Eaton on December 27, 1976, concerning the test.

After the 181 Mg (200 tons) of pellets had aggregated at the California plant, they were loaded into box cars which were routed to Charleston, South Carolina. Then, after a delay with the pellets unprotected, the box cars proceeded to Rantoul, Illinois, where the pellets were unloaded and delivered to Chanute Air Force Base. Upon their arrival at the boiler site, the pellets had so deteriorated that the RDF was mostly fines, and the remaining pellets had rough sides rather than the smooth sides characteristic of newly formed pellets.

When the 181 Mg (200 tons) of deteriorated dRDF were placed in bunkers to a depth of 7.9 meter (26 feet), the fuel bridged and rat holed. Since the sides of the rat hole were stable, bins were unloaded by flushing the bunkers with a fire hose. After 3 weeks of storage, the dRDF ignited by spontaneous combustion. While bunker flooding with water extinguished the fire, much of the remaining dRDF had deteriorated further.

Boiler and Furnace Facility

The Chanute Air Force Base heating plant houses several low-pressure saturated steam boilers fired with chain grate stokers. The wind box is unsegmented, and the front and rear overfire air jets are modulated as a battery. The overhead parabolic bunkers feed a weigh lorry.

Test Program

After the bunkers were unloaded, some pellets were salvaged for short-duration tests. During these tests (fired at 100 percent pellets), the chain grate could not be fed fast enough to maintain load. Also, since the fire filled the front of the furnace, the pellets burned too rapidly. No further information on these tests was acquired.